DOE/NASA/0226-1
NASA CR-165262

A Computer Simulation of the Transient Response of a 4 Cylinder Stirling Engine with Burner and Air Preheater in a Vehicle

(NASA-CR-165262) A COMPUTER SIMULATION OF THE TRANSIENT RESPONSE OF A 4 CYLINDER STIRLING ENGINE WITH BURNER AND AIR PREHEATER IN A VEHICLE Final Report (Martini Engineering) 182 p HC A09/MF A01 N81-22313 G3/34 Unclas 42155

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March 1981

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Under Contract DEN3-226

for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs

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1.0 ABSTRACT

A series of computer programs are presented with full documentation which simulate the transient behavior of a modern 4 cylinder Siemens arrangement Stirling engine with burner and air preheater. Cold start, cranking, idling, acceleration through 3 gear changes and steady speed operation are simulated. Sample results and complete operating instructions are given. A full source code listing of all programs are included.

Reasonable results are obtained but the program has not been validated.

2.0 INTRODUCTION

This report presents the complete results of the work done under contract DEN 3-226 by Martini Engineering for NASA-Lewis on the DOE-sponsored Automotive Stirling Engine Program.

In brief, this work consists of preparation of a series of computer programs which simulate the transient operation of a 4 cylinder, double acting Stirling engine like the United Stirling P-40 or P-75 engine. Since the dimensions of these machines are proprietary, the computer program is set up using the General Motors 4L23 engine for which there is complete information.

The boundaries of the simulation, that is, what is evaluated and what is not, is given in Section 3. Section 4 describes the programs in mathematical terms and justifies the equations that are used. After each small section of explanation, a copy of the part of the computer program it explains is given.

Section 5 gives the full listings for two programs. CNTLA is the pre-program to prepare the data file and allow change in input data from the console. CNTLB is the main program that calculates and displays engine operation during the simulation.

Section 6 gives the program users manual which is written to be complete by itself and contains all the operator needs to apply the programs.

Section 7 presents a sample solution using the final program.

Section 8 summarizes what was learned in trying to construct a rapid but accurate simulation program for use in studying control schemes.

3.0 PROBLEM DEFINITION

The computer program presented and explained herein is to simulate the operation of a Stirling engine powered vehicle. The simulation starts with engine and vehicle stopped and at a given ambient temperature. Figure 3.1 shows a schematic of one part of the engine giving the names of the engine parts. The burner is started at full fuel flow. Air flow is made a specified fraction of fuel flow to supply 10% excess air. The flame heats the heater tubes and then heats a plate type counter flow air preheater. One burner is assumed to heat all heater tubes because this is what the United Stirling engines have. It does not matter that the 4L23 uses 4 separate burners. Transient heat up of both engine and air preheater is simulated. A separate preliminary computer program, WARM, was written to separately investigate this part of the engine (see Appendix A). Gas transit times in the burner are neglected. Heat transfer rates are computed from standard correlations. The heater tubes are regarded as one node but the length of the air preheater is divided into as many as 20 nodes. WARM was used to determine the largest reasonable time step as far as the burner and air preheater are concerned. WARM also was used to determine the smallest number of nodes the air preheater can be divided into and still retain adequate accuracy. The computation method found to be accurate by the use of WARM is incorporated into the main program.

Longitudinal heat conduction in the air preheater is simulated. Fuel is assumed not to be preheated. However, the flow rates of the air and flue gas are realistic as is the heat capacity. The thermal heat conductivity and the viscosity of the flue gas is assumed to be the same as air.

The temperature of the gas heater tubes is regulated by proportional control for the engine cycle with a set point and a proportional band. At first, heat is removed from the heater tubes only by conduction to the other metallic parts of the engine. Since this is the chief heat leak when the engine is stopped, other heat conduction paths, like through the insulation, are ignored since these would be much less.

After the burner has been on for a specified time period, the engine is cranked for a specified time period with a specified torque. At the same time a timing valve opens up to add gas to each working space in turn during the time that that particular working space is expanding. Under the influence of these two forces, the engine accelerates to idling speed that is specified. As the idling speed is reached, the engine pressure is adjusted to keep this idling speed.

Next, the clutch is engaged. To simulate this, the ratio of meters traveled by the vehicle per engine revolution changes smoothly over a short time from zero to a new specified value. Provision is made for the gear ratio to change smoothly as two higher vehicle speeds are reached to simulate gear changes in a normal automobile. At the same time the required vehicle speed is put on a ramp to the cruise speed at the end of a specific acceleration time. Gas is added to each cylinder in turn as long as the vehicle speed falls short of the required vehicle speed for that time. Control is by proportional band operating on the flow resistance between the high pressure reservoir and each of the working gas spaces in turn when the vehicle speed

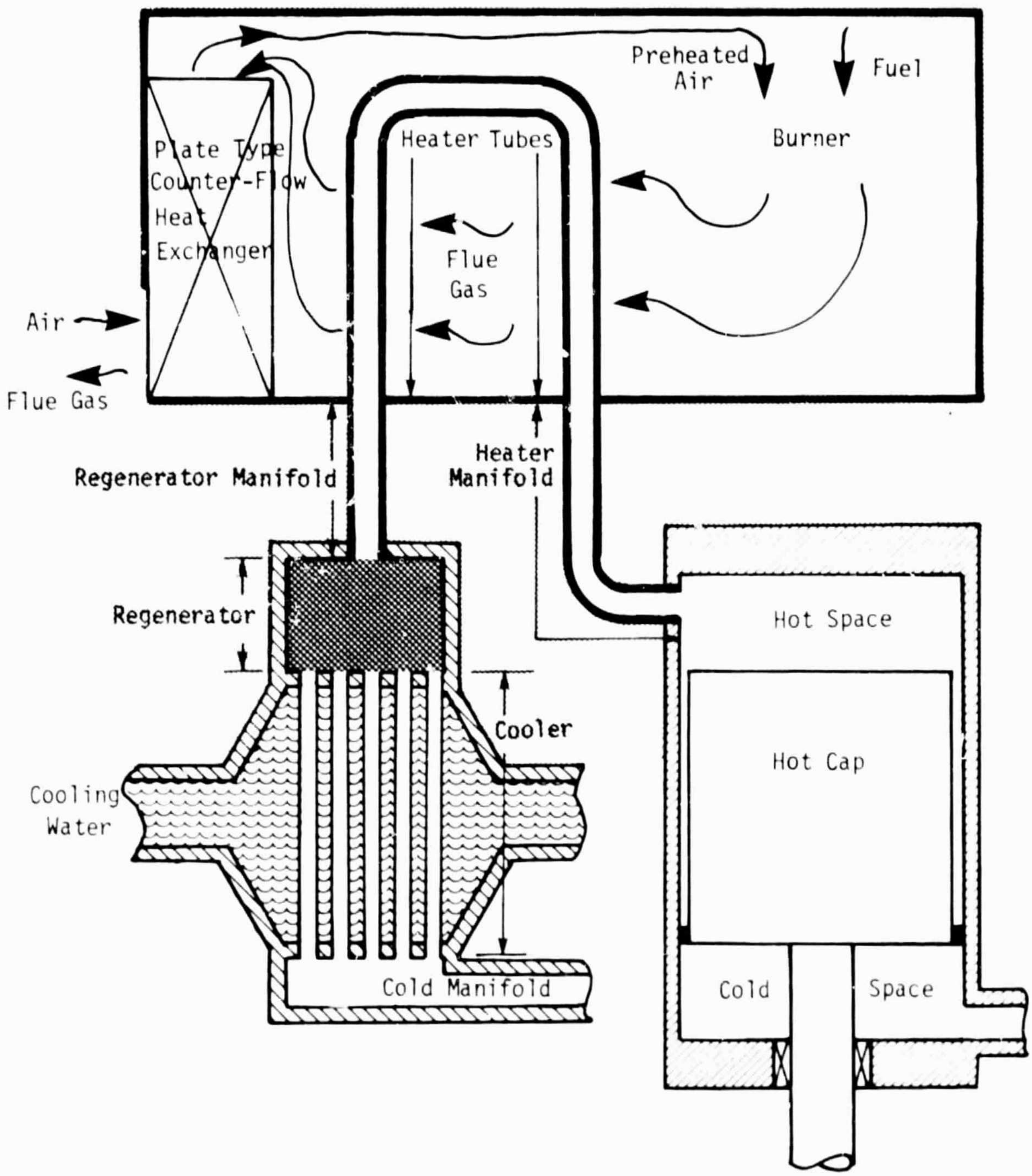

Figure 3.1. Schematic of Engine Simulation (one of 4 cylinders).

is less than the scheduled speed. If the vehicle speed is more than the scheduled speed, then the flow resistance is between each one of the working spaces in turn and the low pressure reservoir.

At the end of the acceleration phase the pressure in the engine is adjusted by proportional control to keep the vehicle going as close as possible to the specified cruise speed. In order to check the calculation method, the time for cruise should be long enough so that the engine and vehicle attain steady state operation. Only at this point can calculated power output and efficiency be possibly compared with validated power output and efficiency data from the literature.

The above describes a simple driving cycle. Of course, more complicated cycles can be traced by changing the program. Also, more complicated control schemes than simple proportional control can be incorporated.

This section has described the problem in qualitative terms to describe in a non-technical way what is being attempted to be calculated. Now Section 4 will present the equations used in the solution and justify them.

4.0 MATHEMATICAL METHOD OF SOLUTION

This section presents the equations used in the analysis and justifies them.

During the development of this program the burner, heater tubes and air preheater were evaluated separately to determine how many nodes there need be in the air preheater and what time step is needed to adequately simulate this part of the machine. (See Appendix A.) Once these values were determined, the computational part of the program was incorporated into the main program. The burner and air preheater will be discussed in its proper order in the main program.

The main program has been divided into two parts because of memory limitation of the Altos computer used by Martini Engineering to write the program. The first part, CNTLA, allows any input parameter to be changed and then intermediate results are calculated. The parameters needed for the main calculation are filed. Then the main program, CNTLB, is brought in. The intermediate results are read in and the simulation proceeds.

Directions for use of the program and how to change input conditions are given in Section 6.

4.1 CNTLA

The flow diagram is given in Figure 4.1. The base case is recorded in data statements. Any input value can be changed by keying in the input number, a space and then a new value with a decimal point. See Section 6 for additional directions. The new input value is read in from the console as QQ and then is given the proper identity.

The input numbers were assigned as the program grew. Therefore, Section 6 gives the identity of the input numbers and what the base case values are. One table gives them in numerical order. The other gives them organized by operating condition and dimensions for the different parts of the machine. For the software available to the Altos computer for high speed computation, only real numbers in fixed point format (no integers) can be read out of the file FORT10.DAT.

The complete listing of CNTLA.FOR is given in Section 5.

4.2 CNTLB

CNTLB does all the computations. Figure 4.2 gives the overall flow chart for this program. The input data are read in from the file. The output conditions are set. Values are initialized that could not be conveniently done in CNTLA. Then if the graphic option is selected, the borders and the schedule of temperature pressures, engine speeds and vehicle speeds are displayed.

Next the engine and vehicle control subprogram is put all in one place so far as possible so that changes can be made more easily. This program increments the time and keeps track of the driving cycle schedule. It calls in the other elements of the computational part of the program as needed. These computational parts need not be subroutines since the return point is

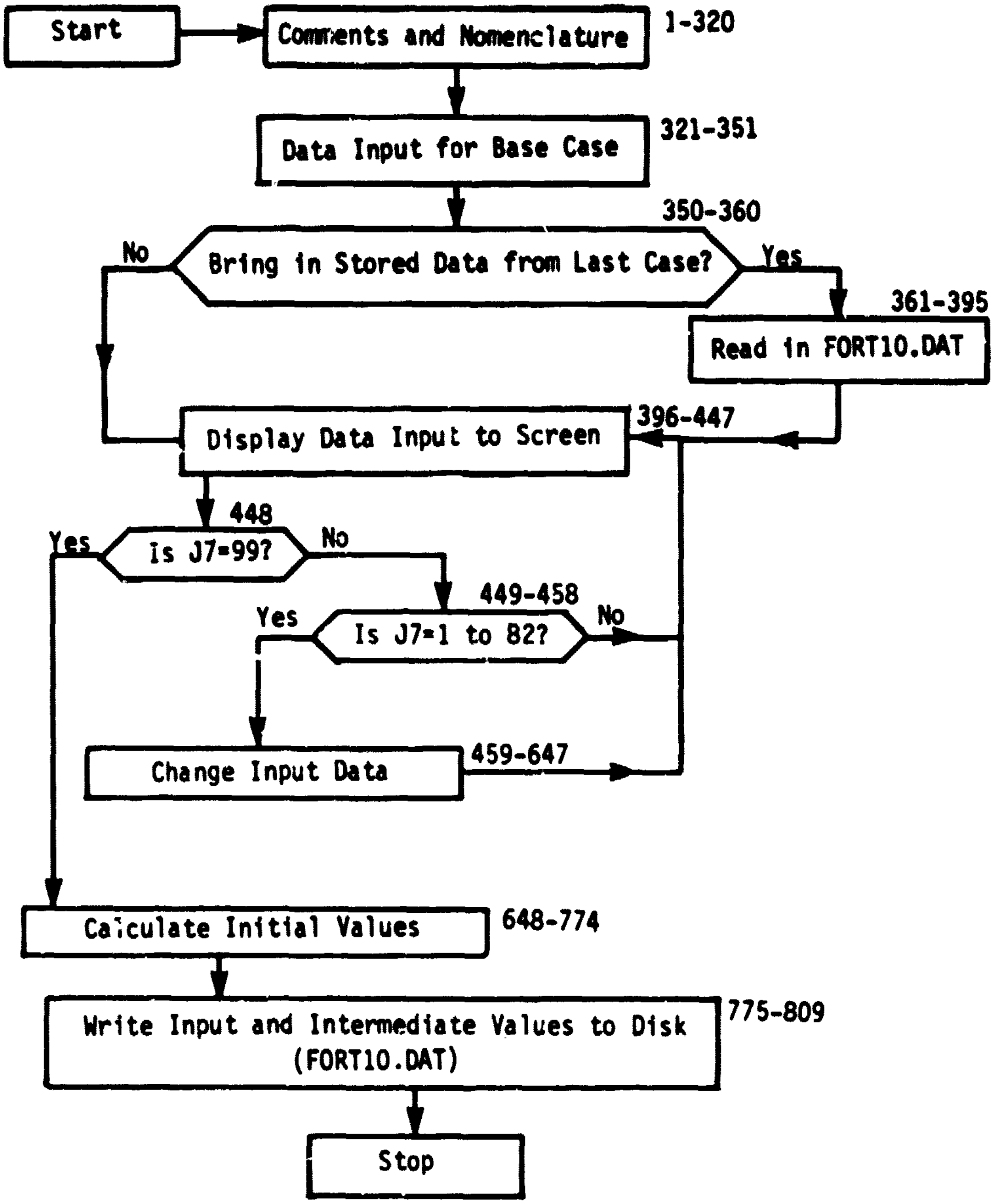

Figure 4.1. Flow Chart for CN?LA (numbers refer to line number for listing in Section 5)

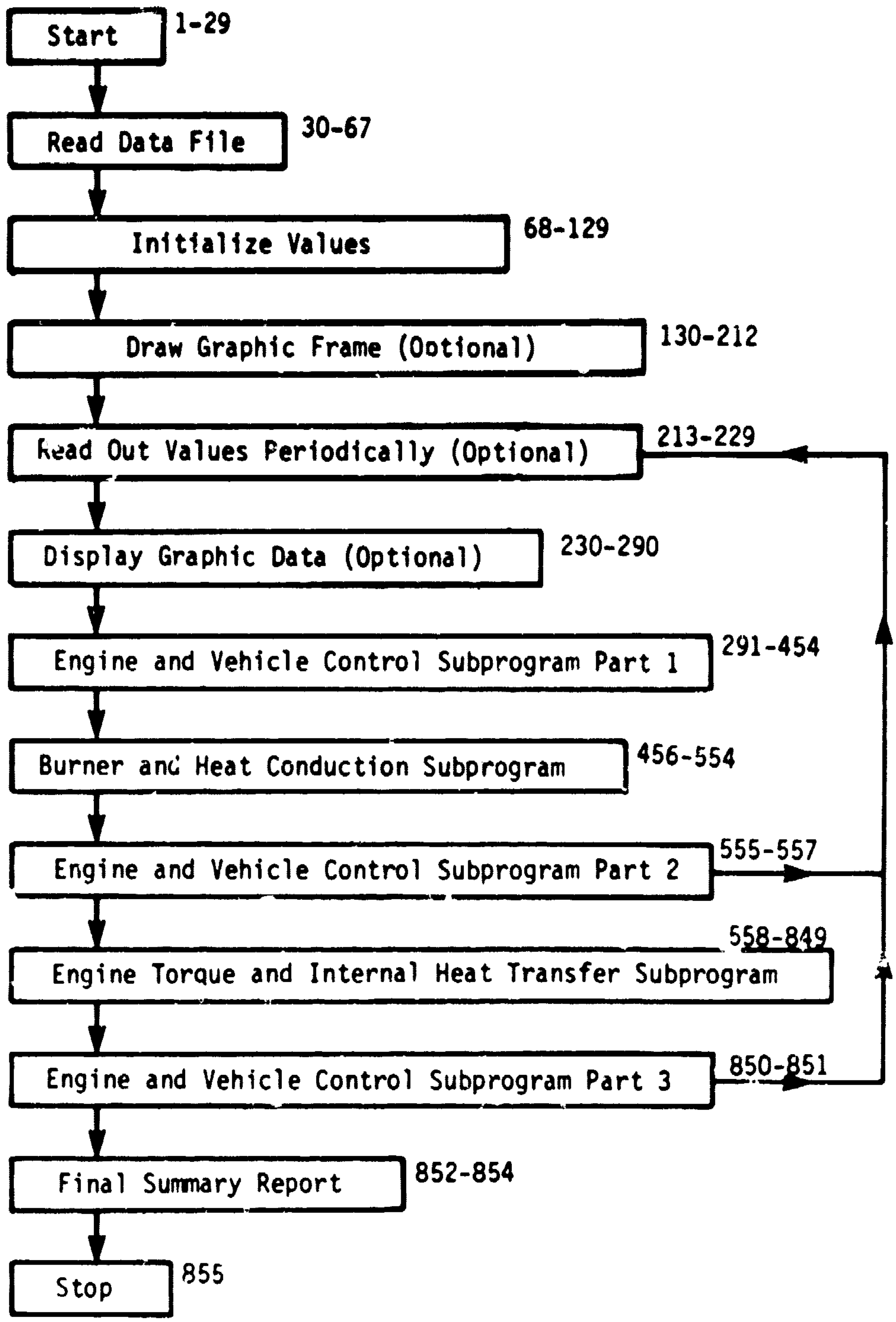

Figure 4.2. Overall Flow Chart for CNTLE (numbers refer to line number from listing in Section 5 and throughout the rest of Section 4.1).

always the same. At first only the burner and heat conduction subprogram is used. Then when the engine starts rotating, the engine torque and internal heat transfer subprogram is also used.

If the total time set for the solution is not exceeded, the program repeats starting with the engine and vehicle control. If time is complete, the program stops and a brief summary is printed out. The full listings of both CNTLB and CNTLA are given in Section 5. In this section CNTLB is explained fully. The full program is divided into small sections according to the flow chart of Figure 4.2. For clarity, each small section of explanation is followed by the part of the program it explains.

4.2.1 Read Transfer File (Lines 1 to 67)

Besides comments about purpose of program and dimension and type and data statements, the transfer file FORT10.DAT is read from the disc. This read statement must be exactly parallel to the write statement in CNTLA. Symbols are defined in CNTLA (see page 73).

```
 1:  C ************PROGRAM CNTLB.FOR********************************
 2:  C WRITTEN BY MARTINI ENGINEERING UNDER CONTRACT NUMBER
 3:  C DEN3-226 FOR NASA-LEWIS UNDER THE DOE ADVANCED AUTOMOTIVE
 4:  C PROPULSION PROGRAM.  CNTLB READS IN THE INPUT DATA FILE
 5:  C GENERATED IN CNTLA AND CALCULATES AND DISPLAYS RESULTS.
 6:  C CNTLB CALCULATES THE TRANSIENT PERFORMANCE OF A 4 CYLINDER
 7:  C DOUBLE ACTING STIRLING ENGINE WITH TUBULAR HEAT EXCHANGERS
 8:  C AND POROUS REGENERATOR CONNECTED TO A VEHICLE THROUGH A GEAR BOX.
 9:  C THE RESIDENT DRIVING CYCLE CONSISTS OF HEATUP,CRANKING,IDLE,
10:  C ACCELERATION FROM ZERO TO CRUSE SPEED AND HOLD THAT SPEED.
11:  C SECOND AND THIRD GEAR CHANGES ARE SPECIFIED BASED UPON VEHICLE
12:  C SPEED. GEAR CHANGE IS LINEAR WITH A SPECIFIED TIME.
13:  C CNTLA USES AS A BASE CASE THE DIMENSIONS OF THE 4L23 ENGINE.
14:  C CNTLB ADJUSTS THE TIME STEP SO THAT THE ANGLE INCREMENT IS
15:  C BETWEEN 7 AND 30 DEGREES. THE PROGRAM HAS NO LIMIT TO FLOW
16:  C ACROSS GAS NODES OR CHANGE IN GAS INVENTORY.  CONTROL IS BY
17:  C CHANGE IN GAS INVENTORY.
18:  C          ***** START OF PROGRAM *****
19:             DIMENSION XT(4),IPV(2,4),JPV(2,4),
20:        1    P2(4),P3(4,8),P4(4),M(4),FP(4),TQ(4),VHA(2,4),VCA(2,4),
21:        2    VT(2,4),XX(4),
22:        3    P1(4),CVM(8,4),TGA(2,8,4),
23:        4    QHI(4),T3A(4),TIN(10),EX(8),TOU(10),TM(6,4),EY(8),KME(8),
24:        5    QM(8),TMA(8,4),
25:        6    CM(5)
26:             DIMENSION TM1(6,4),W(2,8,4),CVG(8,4)
27:             REAL LCP,LH,LR,MSH,MW,KK,KR,LC,M,ME,KAR,MGI
28:             REAL LHH,LHV,MWFG,LAPH,MIR,MIR1,LHM,MIV,LRM,M2,MF
29:             REAL NTRM,NTC,NS,NR,NTH,NTHM,IG1,NO,NAPH,KAPH,KM,KMX,KME
30:  C  DATA CONSTANTS
31:             DATA PI4,PI,PI2,RAD,R/0.7854,3.14159,1.57080,0.017453,8.314/
32:             DATA J,CPA,CPFG/5,1.03,1.20/
33:  C***** READ TRANSFER FILE FROM DISK
34:  9004       FORMAT(5(F9.3))
```

```
35:           READ (10,8004)THMG,TPB,TWI,FWI,OM1
36:           READ (10,8004)T1,DT,ME,RGE1,KAPH
37:           READ (10,8004)NTHM,DIHM,FFF,THU,LHM
38:           READ (10,8004)TCR,TID,TAC,TOTT,SPM
39:           READ (10,8004)RC,LCR,DCY,DDR,DIH
40:           READ (10,8004)WTHM,NTH,VHDX,NR,DR
41:           READ (10,8004)LR,FF,NS,MSH,THW
42:           READ (10,8004)VCDX,FCA,DIC,LC,NTC
43:           READ (10,8004)MIV,NTRM,DIRM,AFR,LRM
44:           READ (10,8004)DOH,LHH,TMAPH,LAPH,WAPH
45:           READ (10,8004)TAPH,NAPH,PRL,PRH,WTRM
46:           READ (10,8004)TST,MIR,RAF,NO,LHV
47:           READ (10,8004)CMAPH,AFAPH,RA1,CZ,DEQ
48:           READ (10,8004)UXY,DT2,CY,UXX,CYY
49:           READ (10,8004)FUEL,AMF,AH,CMH,QEX
50:           READ (10,8004)KAR,TIM,VHD,VRD,CMX
51:           READ (10,8004)VCD,VCDA,VTD,XA,XB
52:           READ (10,8004)ACY,BCY,PI32,RC2,CCY
53:           READ (10,8004)EARAD,EADEG,DIST,OMEG,GCT
54:           READ (10,8004)VHA(1,1),VHA(1,2),VHA(1,3),VHA(1,4),VCA(1,1)
55:           READ (10,8004)VCA(1,2),VCA(1,3),VCA(1,4),VT(1,1),VT(1,2)
56:           READ (10,8004)VT(1,3),VT(1,4),CP,CV,MW
57:           READ (10,8004)RX,KK,GA,KR,XC
58:           READ (10,8004)TQV,IQ1,VHM,VRM,RGE2
59:           READ (10,8004)RGE3,VSP2,VSP3,THH,TRH
60:           READ (10,8004)RWT,TCY,THC,G,HCL
61:           READ (10,8004)KM,KMX,THCH,Q1,Q2
62:           READ (10,8004)Q3,EIN,KME(1),KME(2),KME(3)
63:           READ (10,8004)KME(4),KME(5),KME(6),CM(1),CM(2)
64:           READ (10,8004)CM(3),CM(4),CM(5),PBIS,PBVS
65:           READ (10,8004)TREP
66:           WRITE(5,8006)
67:     8006  FORMAT(' FILE READ')
```

4.2.2 <u>Initialize Values</u> (Lines 68-129)

Although most initial values are in the transfer file, it is more convenient to initialize some values in CNTLB. Also since integers cannot be read out of the transfer file due to limitations in the software available, integer values, like N and J, must be made at this point.

```
68:  C*****INITIALIZE VALUES
69:  C ORGANIZE TIMES FOR OPERATING CYCLE
70:           TT=0.
71:           TI1=THU+TCR
72:           TI2=TI1+TID
73:           TI3=TI2+TAC
74:  C   BURNER INITIALIZATION
75:           N=NO
76:           NO2=N/2
```

```
            DO 200 I=1,N
            TOU(I)=T1
            TIN(I)=T1
            EY(I)=T1
      200   EX(I)=T1
            TIN(N+1)=T1
            TA=T1
            TD=THMG-TWI
            FLAME=T1
            TOU(N+1)=T1
            CFL=1000.
            CFH=0.
            CFF=0
C   INITIALIZE CUMULATIVE HEAT INPUT AND METAL TEMPS
            DO 198 I=1,4
            TM(1,I)=T1
            TM(2,I)=T1
            TM(3,I)=T1
            TM(4,I)=T1
            TM(5,I)=(TWI+T1)/2.
            TM(6,I)=TWI
            M(I)=0.0
      198   QHI(I)=0.
C  SET PRINTOUT OPTION
            J=Q2
C  INITIALIZE VEHICLE INERTIA
            VIN=0.0
C  INITIALIZE ENGINE AND VEHICLE SPEED
            OMEG=0.0
            SPV1=0.0
            SPVD=0.0
C  INITIALIZE WORKING TIME STEP
            DDT=DT
C  INITIALIZE TORQUES
            TQS=0.0
            TQV=0.0
            TNET=0.0
C  INITIALIZE ENGINE ANGLES
            EARAD=0.0
            REV=0.0
            NER=0
            NGC=-1
            MIR1=0.
            RGE=0.
C INITIALIZE ENGINE PRESSURE
            DO 950 I=1,4
      950   P1(I)=PRL
C  INITIALIZE FLAG TO CALCULATE CONDITIONS AT CRANKING
            IG2=0
C  INITIALIZE OUTPUT FLAGS
            POF=0.0
            GDF=0.0
            GDI=TOTT/1024.
```

4.2.3 Draw Graphic Frames (Lines 130-212)

The ADM-3 terminal with the Retrographics package can have two output overlayed on the screen at the same time, a graphic output and an alphanumeric output. The graphic output,if it is used, cannot easily be turned off. The alphanumeric output to the screen can be turned off so just the graphic display is visible. It is much easier to understand what is going on with the graphic display. In the case where the graphic display is not used, the output will be stored in a file which may be read back and possibly plotted off line.

The contract requires that the main program, CNTLB, should run without manual intervention during program execution. Therefore, the decisions on how the results of CNTLB are read out are changable in CNTLA and are fed to CNTLB in the transfer file.

The flag Q1 must be 1.0 if graphic output is to be used. At this point the outline of the graphic display and the schedule of how the driving cycle should go are displayed on the screen. Figure 4.3 shows how the screen is divided up. The retrographics modification to the ADM-3A terminal is capable of displaying 250 points vertically and 512 points horizontally. However, the package is compatible with Tektronics Plot 10 software which has 780 points vertically and 1024 points horizontally. These latter numbers are used to specify location. The subroutine VECTOR draws a line on the screen (see Appendix C).

The arrangement evolved as experience was gained with the solution. Space for the four working space pressure-volume (PV) diagrams was particularly useful in observing what is going on with the solution.

```
130:  C******** DRAW GRAPHIC FRAME IF OPTION IS ON
131:  C  GRAPHIC FRAME
132:          IF(Q1-1.00)158,157,158
133:  C  DRAW OUTLINE
134:  157     CALL CLEAR
135:          I1=0
136:          J1=0
137:          I2=1023
138:          J2=0
139:          CALL VECTOR(I1,J1,I2,J2)
140:          I1=1023
141:          J1=779
142:          CALL VECTOR(I2,J2,I1,J1)
143:          I2=0
144:          J2=779
145:          CALL VECTOR(I1,J1,I2,J2)
146:          I1=0
147:          J1=0
148:          CALL VECTOR(I2,J2,I1,J1)
149:          I1=700
150:          J1=0
151:          I2=700
152:          J2=779
153:          CALL VECTOR(I1,J1,I2,J2)
154:  C  DIVIDE INTO 4 LAYERS LEFT SIDE
```

```
      I1=0
      J1=629
      I2=700
      J2=629
      CALL VECTOR(I1,J1,I2,J2)
      J1=479
      J2=479
      CALL VECTOR(I1,J1,I2,J2)
C DIVIDE INTO FOUR LAYERS, RIGHT SIDE
      I1=700
      J1=190
      I2=1023
      J2=190
      CALL VECTOR(I1,J1,I2,J2)
      J1=380
      J2=380
      CALL VECTOR(I1,J1,I2,J2)
      J1=570
      J2=570
      CALL VECTOR(I1,J1,I2,J2)
C DRAW SCHEDULED VEHICLE SPEED
      I1=0
      J1=632
      I2=TI2/TOTT*700
      J2=632
      CALL VECTOR(I1,J1,I2,J2)
      I1=TI3/TOTT*700
      J1=776
      CALL VECTOR(I2,J2,I1,J1)
      I2=700
      J2=776
      CALL VECTOR(I1,J1,I2,J2)
C DRAW SCHEDULED ENGINE SPEED
      I1=0
      J1=482
      I2=THU/TOTT*700
      J2=482
      CALL VECTOR(I1,J1,I2,J2)
      I1=THU/TOTT*700
      J1=554
      I2=TI2/TOTT*700
      J2=554
      CALL VECTOR(I1,J1,I2,J2)
C DRAW HOT METAL GOAL TICK (THMG)
      I1=0
      J1=200
      I2=10
      J2=200
      CALL VECTOR(I1,J1,I2,J2)
C DRAW COOLING WATER TEMP TICK (TWI)
      J1=10
      J2=10
      CALL VECTOR(I1,J1,I2,J2)
C CALCULATE DISPLAY PARAMETERS
      PDIF=PRH
      XLOW=VTD+VHDX+VCDA
      XDV=(ACY+BCY)*RC2
  158 CONTINUE
```

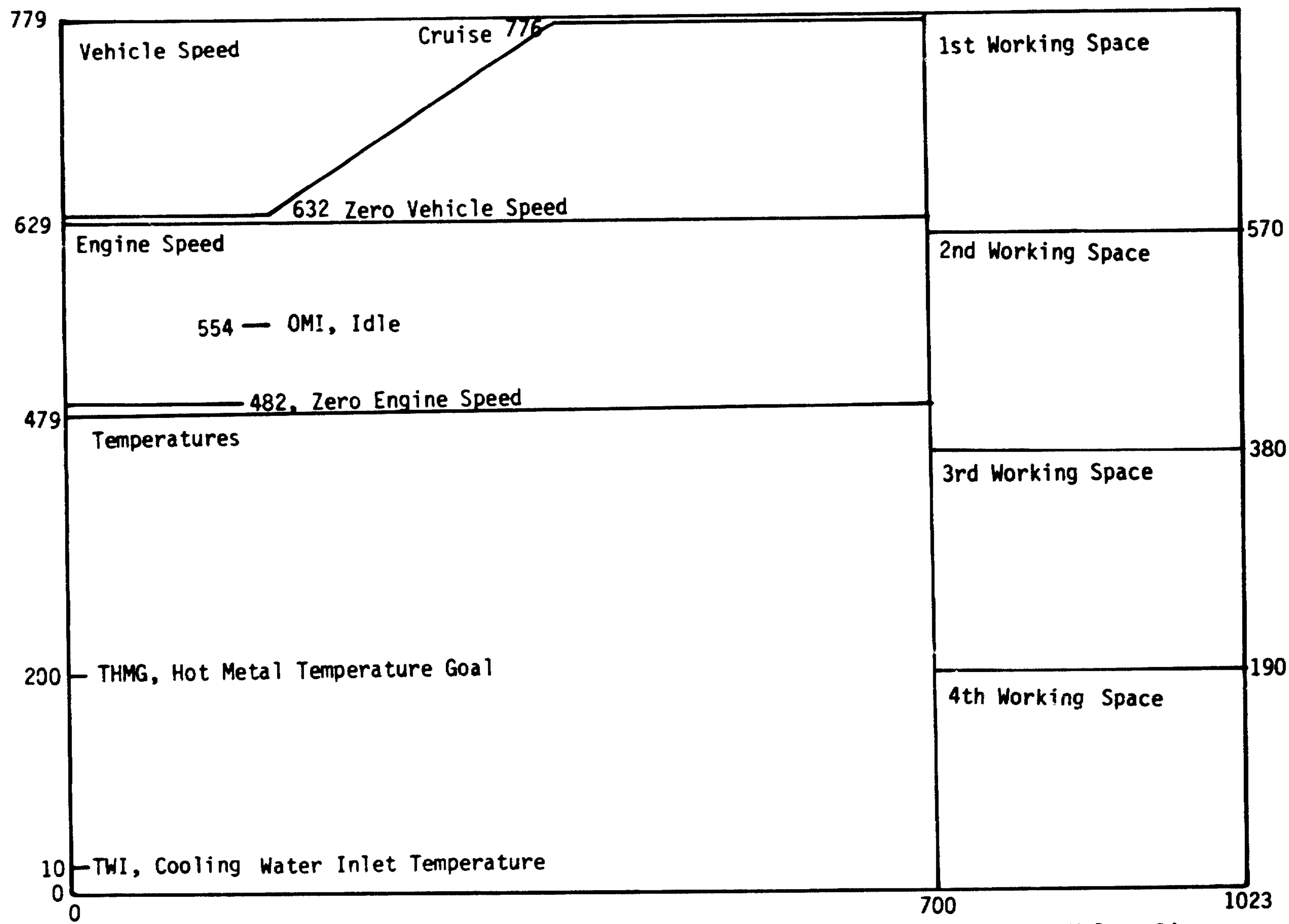

Figure 4.3. Graphic Display Scheme.

4.2.4 Write Unified Printout (Lines 213-229)

The unified printout is placed first in the main loop of the program so that the initial conditions can be displayed. The readout may either be to the screen (Q2 = 5.0) or to the printer (Q2 = 2.0). This option is changed from CNTLA. Then in Line 101 of CNTLB the integer J is set from the real value Q2. The format of the readout is nine columns but not all are filled. The key to the readout is given in the Program Users Manual (Section 6).

Note that this printout is optional. It is enabled when Q3 = 1.0. This flag can be changed from CNTLA. If the graphic readout gives all the information desired, then it greatly speeds up the calculation by having the printout infrequently.

The value TREP can be set from CNTLA to control the repetition time for this printout.

```
213:  C*****WRITE UNIFIED PRINTOUT--RETURN POINT FOR MAIN LOOP
214:  401       IF(Q3-1.0)390,402,390
215:  402       IF(TIM-POF)390,391,391
216:  391       POF=POF+TREP
217:            WRITE(J,8025)TIM,CFF,REV,OMEG,SPV1,SPVD,DDT
218:  8025      FORMAT(6F8.2,F8.5,2F8.2)
219:            WRITE(J,8022)TIN(1),TIN(2),TIN(3),TIN(4),TIN(5),TIN(6),TIN(7),
220:           1 TIN(8),TIN(9)
221:            WRITE(J,8022)EX(1),EX(2),EX(3),EX(4),EX(5),EX(6),EX(7),
222:           1 EX(8),FLAME
223:            WRITE(J,8022)TOU(1),TOU(2),TOU(3),TOU(4),TOU(5),TOU(6),TOU(7),
224:           1 TOU(8),TOU(9)
225:            DO 10 I=1,4
226:  10        WRITE(J,8022)TM(1,I),TM(2,I),TM(3,I),TM(4,I),TM(5,I),P1(I),
227:           1 M(I),VT(1,I)
228:  8022      FORMAT(9(F8.2))
229:            WRITE(J,8022)TNET,TQS,TQV,VIN,MIR1,RQE
```

4.2.5 Display Graphic Data (Lines 230-290)(Optional)

The display offers a fast and comprehensible way of showing what is going on during the solution. To speed the solution, the display does not print every time step. The total time, TOTT, is divided by 1024, the number of horizontal addresses for plotting to give the graphic display interval, GDI, in seconds. (See line 129.) Therefore, the display programming from line 233 to 277 only is called upon 1024 times during the solution at a regular time interval. There could be 1024 different points if a Tektronix terminal were used. With the ADM-3 Retrographics package used in development of this program, 512 horizontal points are plotable. Therefore, two dots are possible in the vertical direction for every plotable point in the horizontal direction.

The following displays are shown:

A. From the beginning

1. current fuel flow rate (over full height of display)
2. average heater metal temperature
3. flue gas leaving heater and entering preheater
4. flue gas leaving preheater
5. average of metal node 1 (around hot spaces)
6. average of metal node 4 (at the hot end of the regenerators)
7. average of metal node 5 (at the middle of the regenerators)

B. After engine starts to be cranked (see line 269)

8. engine speed
9. vehicle speed

The above displays are plotted 1024 times during the solution or twice for every displayable point using the Retrographics package.

```
230:  C*****DISPLAY GRAPHIC DATA,PART 1
231:  390       IF(Q1-1.)20,21,20
232:  C CHECK TO SEE IF PLOTTING SHOULD BE DONE
233:  21        IF(TIM-GDF)20,393,393
234:  393       GDF=GDF+GDI
235:  C SHOW FUEL FLOW RATE
236:            I1=TIM/TOTT*700
237:            J1=CFF/FFF*777
238:            CALL POINT(I1,J1)
239:  C SHOW AVERAGE HEATER TEMP.
240:            J1=(TA-TWI)/TD*190+10
241:            CALL POINT(I1,J1)
242:  C SHOW FLUE GAS TEMP. ENTERING PREHEATER
243:            J1=(TOU(N+1)-TWI)/TD*190+10
244:            CALL POINT(I1,J1)
245:  C SHOW FLUE GAS TEMP. LEAVING PREHEATER
246:            J1=(TOU(1)-TWI)/TD*190+10
247:            CALL POINT(I1,J1)
248:  C SHOW AVE. HOT METAL SPACE TEMP (NODE #1)
```

```
249:           X=0
250:           DO 145 I=1,4
251:  145      X=TM(1,I)+X
252:           X=X/4.
253:           J1=(X-TWI)/TD*190+10
254:           CALL POINT(I1,J1)
255:  C SHOW AVE METAL TEMP HOT END REGEN. (NODE #4)
256:           X=0
257:           DO 146 I=1,4
258:  146      X=TM(4,I)+X
259:           X=X/4.
260:           J1=(X-TWI)/TD*190+10
261:           CALL POINT(I1,J1)
262:  C SHOW AVE. METAL TEMP. MIDDLE REGEN. (NODE #5)
263:           X=0
264:           DO 147 I=1,4
265:  147      X=TM(5,I)+X
266:           X=X/4.
267:           J1=(X-TWI)/TD*190+10
268:           CALL POINT(I1,J1)
269:           IF(TIM-THU)20,20,954
270:  C SHOW ENGINE SPEED
271:  954      J1=OMEG/OM1*72+482
272:           CALL POINT(I1,J1)
273:           IF(TIM-TI2)20,20,953
274:  C SHOW VEHICLE SPEED
275:  953      J1=SPV1/SPM*144+632
276:           CALL POINT(I1,J1)
277:  20       CONTINUE
```

The final part of the graphic data display involves the drawing of four pressure-volume curves for the four working spaces. These curves are drawn only when the flag Q1 = 1. and the time, TIM, is greater than THU. That is, the curves are drawn only when the engine should be moving. The initial engine pressures plot number is calculated on line 320 and the initial volume plot number is calculated on line 340. These are only calculated once. Starting with these values, the next values of these two numbers are calculated on lines 284 and 285. With the initial and next value for both pressure and volume for all four working volumes, four lines (vectors) are drawn (line 286). In lines 287 and 288 the next values become the initial values for the next time around. This part of the program draws four continuous lines tracing out the work diagram for each working space.

```
278:  C*****DISPLAY GRAPHIC DATA, PART 2
279:  C PLOTTING FOR EVERY TIME STEP OF 4 P-V DIAGRAMS
280:  C CHECK TO SEE IF OPTION IS ON
281:              IF(Q1-1.)852,853,852
282:  853         IF(TIM-THU)852,852,854
283:  854         DO 985 I=1,4
284:              IPV(2,I)=(CVM(8,I)-XLOW)*323/XDV+700
285:              JPV(2,I)=P1(I)*190/PDIF+190*(4-I)
286:              CALL VECTOR(IPV(1,I),JPV(1,I),IPV(2,I),JPV(2,I))
287:              IPV(1,I)=IPV(2,I)
288:              JPV(1,I)=JPV(2,I)
289:  985         CONTINUE
290:  852         CONTINUE
```

After every five cycles, the screen area where the work diagrams have been drawn is erased. (See lines 365-372.)

4.2.6 <u>Engine and Vehicle Control Subprogram (EVCS)--Part 1</u> (Lines 291-455)

Figure 4.4 shows the overall flow chart for CNTLB with more particulars given to the engine and vehicle control program than was given in Figure 4.2. The first decision point is to determine whether the cumulative time, TIM, has reached or exceeded THU, the specified heat up time. If it has not, the flag IG1 is set at zero. The program jumps directly to increment the time. The burner and conduction subprogram is executed. This calculates conduction and external heat transfer in the air preheater and to the gas heater of the engine (see Section 4.2.7). After this, the flag IG1 is tested (Part 2). Since it is less than 1, the program jumps back to the readout and display and starts through again.

```
291:  C*****ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
292:  C CHECK TO SEE IF HEAT UP TIME IS EXCEEDED
293:              IF(TIM-THU)503,502,502
294:  503         IG1=0
295:              GOTO 501
```

Eventually, the air preheater and engine get partially heated up when TIM exceeds THU. At this point if this is the first time through, the engine gas inventories are calculated based upon the specified low gas reservoir pressure , the volumes at zero engine angle and gas temperatures in the different parts which are assumed to be equal to the metal node temperatures at that time. Also, the time step is reduced by a factor of 10 to start out (lines 300-301). However, the time step is finally adjusted in lines 351-357.

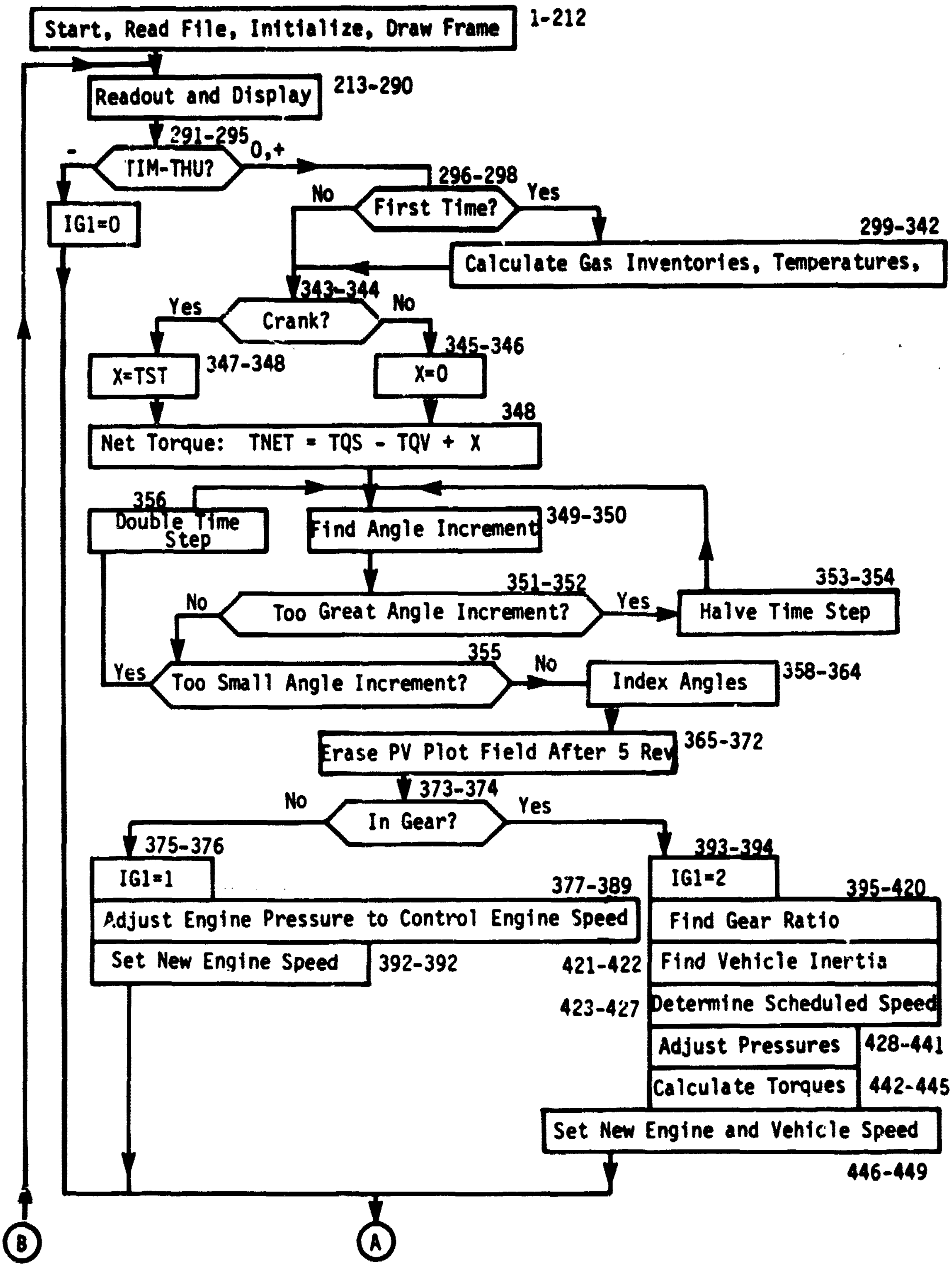

Figure 4.4. Overall Flow Chart of CNTLB with Empahsis on Engine and Vehicle Control Subprogram.

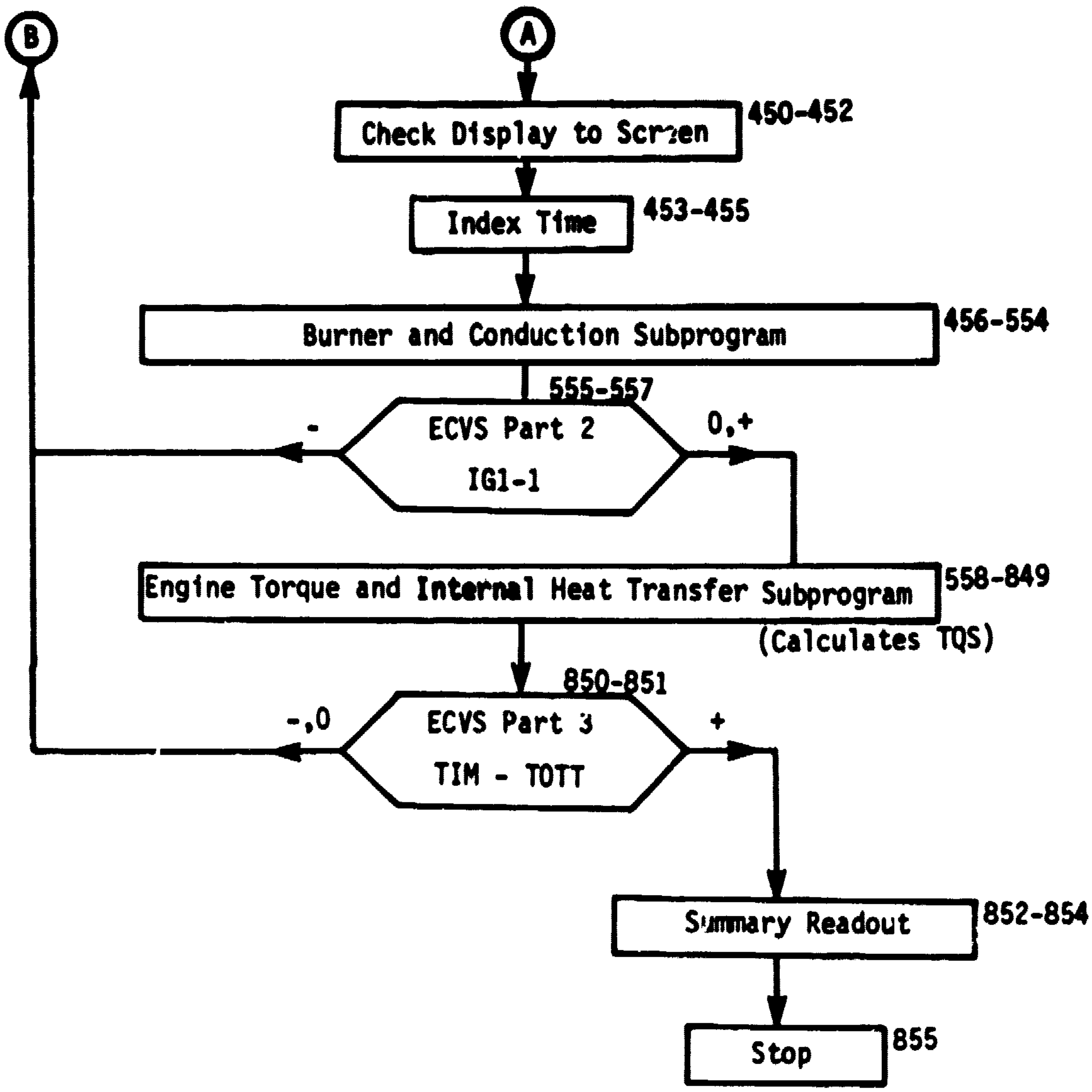

Figure 4.4. Part 2.

```
C FIRST TIME CALCULATION OF GAS MASSES AND INITIALIZE PRESSURES
C   AND SET GAS TEMPS. TO CURRENT METAL NODE TEMPS.
502     IF(IG2-1)504,506,506
504     IG2=1
C REDUCE TIME STEP AT START OF CRANKING
        DDT=DDT/10.
        X=PRL*MW/R
        DO 507 I=1,4
C NODAL GAS MASSES
        W(1,1,I)=X*VHA(1,I)/TM(1,I)
        W(1,2,I)=X*VHM*2./(TM(1,I)+TM(2,I))
        W(1,3,I)=X*VHD*2./(TM(3,I)+TM(2,I))
        W(1,4,I)=X*VRM*2./(TM(4,I)+TM(3,I))
        W(1,5,I)=X*VRD/(TM(5,I)+TM(4,I))
        W(1,6,I)=X*VRD/(TM(6,I)+TM(5,I))
        W(1,7,I)=X*VCD/TWI
        W(1,8,I)=X*VCA(1,I)/TWI
C TOTAL GAS MASSES
        M(I)=0.
        DO 980 K=1,8
980     M(I)=M(I)+W(1,K,I)
C PRESSURES
        P1(I)=PRL
C INITIAL PRESSURE PLOT PARAMETERS
        JPV(1,I)=(P1(I)-PRL)*195/PDIF+195*(4-I)
C AVERAGE GAS AND METAL TEMPERATURES
        TGA(1,1,I)=TM(1,I)
        DO 981 K=2,6
        TMA(K,I)=(TM(K-1,I)+TM(K,I))/2.
981     TGA(1,K,I)=TMA(K,I)
        TMA(7,I)=TWI
        TMA(8,I)=TWI
        TGA(1,7,I)=TWI
        TGA(1,8,I)=TWI
C CUMULATIVE GAS VOLUMES
        CVG(1,I)=VHA(1,I)
        CVG(2,I)=CVG(1,I)+VHM
        CVG(3,I)=CVG(2,I)+VHD
        CVG(4,I)=CVG(3,I)+VRM
        CVG(5,I)=CVG(4,I)+VRD/2.
        CVG(6,I)=CVG(5,I)+VRD/2.
        CVG(7,I)=CVG(6,I)+VCD
        CVG(8,I)=VT(1,I)
C VOLUME PLOT PARAMETERS
        IPV(1,I)=(CVG(8,I)-XLOW)*323/XDV+700
507     CONTINUE
506     CONTINUE
```

If TIM is between THU and THU + TCR, the engine is cranked and a torque, TST, is applied to the engine. The net torque accelerating the engine is this torque, when it is applied, plus TQS, the shaft torque realized by the engine pressures and the position of the pistons inside the engine and minus TQV, the retarding torque at the shaft due to the rolling resistance and the air resistance of the vehicle. At first, the only torque causing motion is TST. As gas is added to the engine, TQS becomes a factor. After the car starts moving, TQV also becomes a factor.

```
343:  C TEST TO SEE IF ENGINE SHOULD BE CRANKED
344:            IF(TIM-(THU+TCR))508,509,509
345:  509       X=0.0
346:            GOTO 511
347:  508       X=TST
348:  511       TNET=TQS-TQV+X
```

Based upon the net torque, the engine will move a certain number of degrees. The general formula is:

$$\underset{\text{Newton-meters}}{\text{Net Torque}} = \underset{\text{Kg m}^2}{\begin{pmatrix}\text{Effective Moment}\\ \text{of Inertia}\end{pmatrix}} * \underset{\text{radians/sec}^2}{\begin{pmatrix}\text{Angular}\\ \text{Acceleration}\end{pmatrix}}$$

Since a Newton is the force required to accelerate one Kg at the rate of one meter per second per second, the above equation checks dimensionally.

Assume that the engine is idling and the engine itself has a moment of inertia, EIN. Let A_1, A_2 and A_3 be the crankshaft angle in radians for one time step in the past, the current position and one time step in the future, respectively. Thus,

$$\text{TNET} = \text{EIN}\ \frac{\frac{A_3 - A_2}{\text{DDT}} - \frac{A_2 - A_1}{\text{DDT}}}{\text{DDT}}$$

The angular velocity OMEG is defined at $(A_2 - A_1)/\text{DDT}$, and the angular increment DANG = $A_3 - A_2$. Making these substitutions, one can obtain:

$$\text{DANG} = (\text{DDT})^2\ \frac{\text{TNET}}{\text{EIN}} + \text{DDT(OMEG)}$$

If the car is in gear, the inertia of the vehicle must be converted to effective inertia as seen by the engine. Equate the kinetic energy of the vehicle to the rotational energy of an equivalent flywheel. Thus:

$$\tfrac{1}{2}\ \text{MIV(SPV1)}^2 = \tfrac{1}{2}\ (\text{VIN})\ (\text{OMEG})^2$$

So

$$\text{VIN} = \text{MIV}\left(\frac{\text{SPV1}}{\text{OMEG}}\right)^2$$

The ratio $\frac{\text{SPV1}}{\text{OMEG}} = \frac{\text{RGE}}{2\pi}$

where SPV1 = vehicle velocity beginning of time step, meters/sec
OMEG = engine angular velocity, rad/sec
RGE = meters traveled/engine revolution

The quantity RGE changes as the gears change and is calculated later (lines 395-419). In the general case the equivalent vehicle inertia must be added to engine inertia EIN.

Therefore, the angle increment is calculated by the formula.

```
349:  C CALCULATE ANGLE INCREMENT
350:  512       DANG=DDT**2*TNET/(EIN+VIN)+DDT*OMEG
```

Now that DANG is calculated, we must find out whether it is suitable. During the first part when TIM was less than THU, the time step DDT was chosen to give accurate but rapid calculation of the heat up of the engine and air preheater. When the engine starts to run, not very accurate calculation of engine performance can be had if DANG is more than 0.5236 radians (30°). Therefore, if DANG becomes greater than this, DDT is halved as many times as it takes to become less than 30°. If engine speed should fall during the driving cycle because of a gear change or a specified speed change, there needs to be a way to increase the time step again by doubling it and if necessary, redoubling it till the angle change is at least 7° (0.12217 radian).

```
351:  C ADJUST TIME STEP SO THAT ANGLE INCR. IS >7 AND <30 DEG.
352:            IF(DANG-0.52360)515,515,513
353:  513       DDT=DDT/2.
354:            GOTO 512
355:  515       IF(DANG-0.12217)517,517,516
356:  517       DDT=DDT*2.
357:            GOTO 512
```

Next, the engine angle in both degrees and radians is indexed. If the angle is greater than 360 degrees, the computer won't handle it as accurately so the program should keep it within this range.

```
358:  C INDEX ENGINE ANGLE MEASURES
359:  516       EARAD=DANG+EARAD
360:            EADEG=EARAD/RAD
361:            REV=REV+DANG/(2.*PI)
362:            IF(EADEG-360.)239,240,240
363:  240       EADEG=EADEG-360.
364:            EARAD=EARAD-2.*PI
```

Since this part of the program is entered once per engine revolution, it is a good place to put the erase program. If the graphic option is on (Q1 = 1), the program counts the number of revolutions with the revolution counter, NER. When it reaches 5, it resets the counter and calls ERASE.

```
365:  C ERRASE PV PLOT FIELD AFTER EVERY 5 REVOLUTIONS
366:            IF(Q1-1.)239,151,239
367:  151       IF(NER-5)152,150,150
368:  150       NER=0
369:            CALL ERASE
370:            GOTO 239
371:  152       NER=NER+1
372:  239       CONTINUE
```

The subroutine ERASE will now be explained. This subroutine (lines 887-921) using the conventions for the Retrographics package and presumably for the Tektronics Plot 10 software draws a series of black lines. Each line goes from 2 to 777 in the vertical direction (see Figure 4.3). Each time ERASE is called, a series of black lines are drawn from the horizontal position 710 to 1013. Although the number of plotable points in the horizontal direction is 512 and the addresses are 1023, it would seem that every other address would do a complete erase. It did not. By this means all the pressure-volume diagrams are erased so that one can see where the new ones fall. (See Appendix C for additional explanation of this subroutine.)

```
887:  C SUBROUTINE USED TO ERASE PV DISPLAY FIELD
888:            SUBROUTINE ERASE
889:            INTEGER*1 GS,US,CA,ES,DE,AA,YH,YL,XH,XL
890:            DATA GS,US,CA,ES,DE,AA/29,31,24,27,127,97/
891:            DO 30 JP=710,1013
892:            CALL CONOUT(GS)
893:            CALL CONOUT(ES)
894:            CALL CONOUT(DE)
895:            YH=777/32+32
896:            YL=MOD(777,32)+96
897:            XH=JP/32+32
898:            XL=MOD(JP,32)+64
899:            CALL CONOUT(YH)
900:            CALL CONOUT(YL)
901:            CALL CONOUT(XH)
902:            CALL CONOUT(XL)
903:            DO 10 I=1,200
904:            M=I+1
905:   10       CONTINUE
906:            YH=2/32+32
907:            YL=MOD(2,32)+96
908:            CALL CONOUT(YH)
909:            CALL CONOUT(YL)
910:            CALL CONOUT(XH)
911:            CALL CONOUT(XL)
912:            DO 20 I=1,200
913:            M=I+1
914:   20       CONTINUE
915:            CALL CONOUT(ES)
916:            CALL CONOUT(AA)
917:            CALL CONOUT(US)
918:            CALL CONOUT(CA)
919:   30       CONTINUE
920:            RETURN
921:            END
```

Now that a proper time step has been chosen, the next thing is to determine what should be done with the engine pressure. When the engine is idling, the engine pressure is adjusted to keep the engine speed adjusted to maintain a specified vehicle speed schedule. Therefore, TIM is compared against TI2, the cumulative time in which the engine is put in gear to determine which method is used to adjust pressure and to compute vehicle inertia and vehicle friction (see Figure 4.4).

```
373:  C CHECK TO SEE IF ENGINE SHOULD BE IDLEING OR IN GEAR
374:          IF(TIM-TI2)519,519,520
```

If the engine is idling, IG1 is set to 1. If it is in gear, IG1 is set to 2. So far it makes no difference subsequently whether IG1 is 1 or 2. Possibly later modifications may utilize this.

For the base case driving cycle, the idling comes before the driving. The current engine speed, OMEG, is compared with the specified idling engine speed OM1. The valve setting for the addition or removal of gas is diagrammed in Figure 4.5. Three valves are used in series (see Figure 4.6).

Valve 1. A slide valve which is open between $\pm 45^{\circ}$ from bottom dead center of each piston in the four cylinder array. The opening of these four slide valves relate to the engine angle as follows:

Table 4.1

ENGINE PRESSURE ADJUSTMENT SCHEDULE

Engine Angle degrees	Number of Cylinder with Slide Valve Open	Number of Working Space Having Pressure Adjusted
315 to 45	1	4
45 to 135	4	3
135 to 225	3	2
225 to 315	2	1

Valve 2. A throttle valve which is closed when the engine speed is exactly the desired speed. At a speed difference, PBIS,on either side of the speed goal, the throttle valve becomes full open at MIR.

Valve 3. A switch valve. The throttle valve is connected to the high pressure reservoir. When the engine speed is below the desired speed and to the low pressure reservoir when the engine speed is above the desired speed.

The author feels that this control scheme is reasonably realistic and similar to control schemes actually used. Other control methods can be substituted.

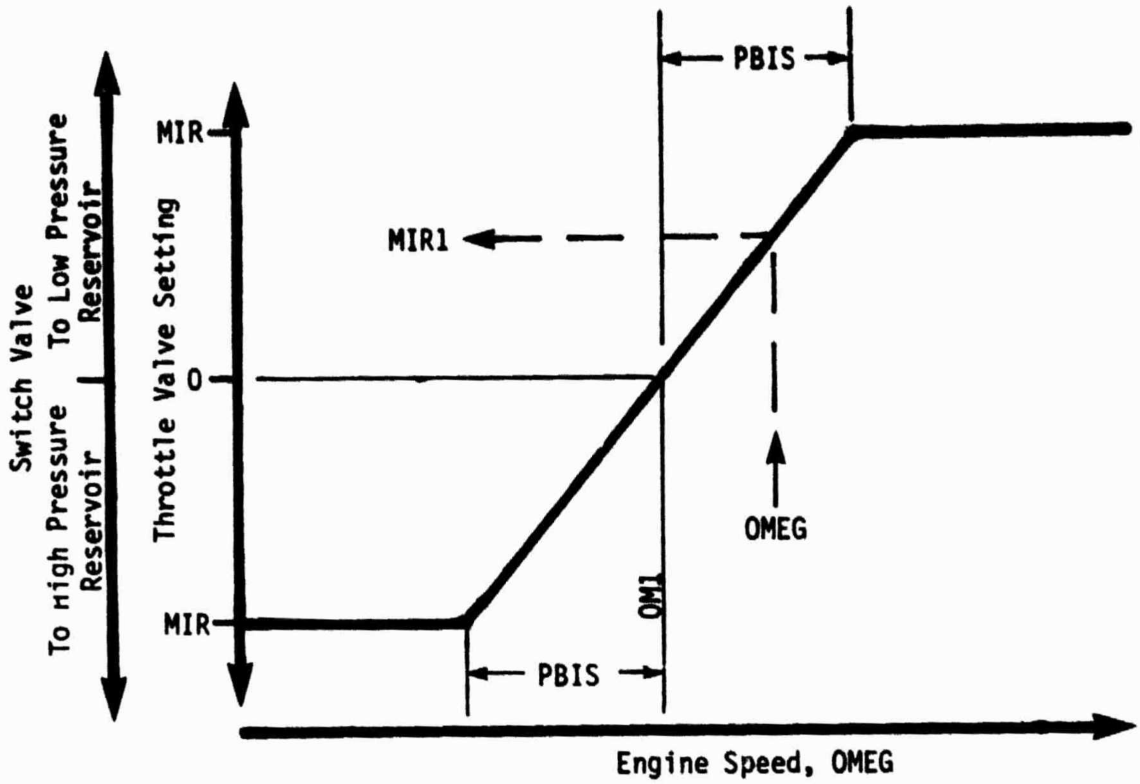

Figure 4.5. Engine Speed Control Scheme.

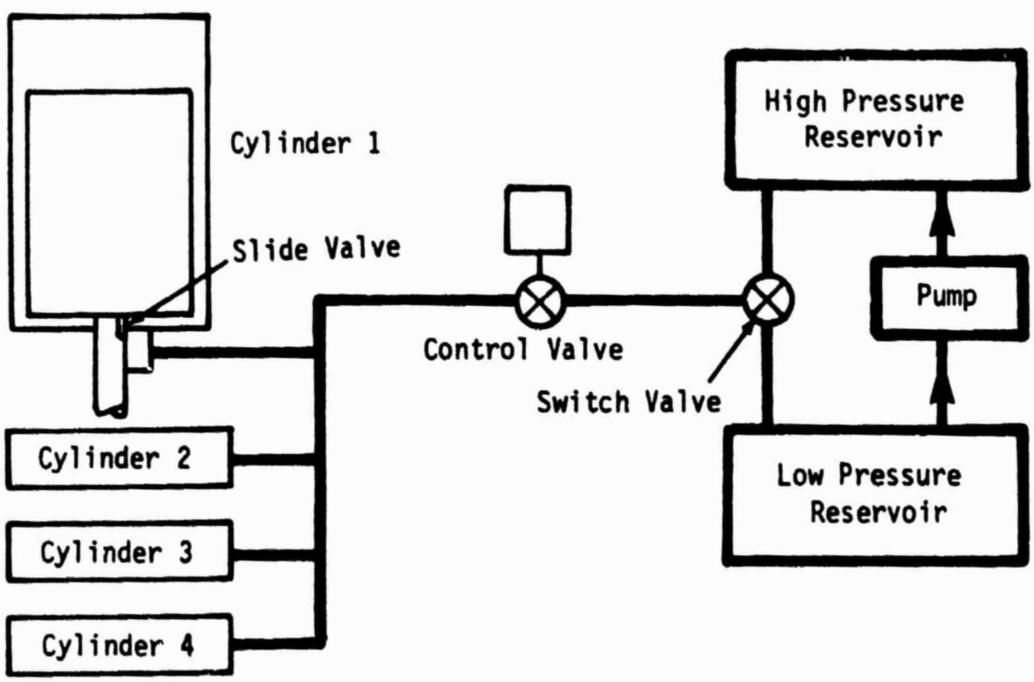

Figure 4.6. Engine Control Valves.

```
375:  C ADJUST ENGINE PRESSURES TO CONTROL SPEED WHILE ENGINE IS IDLEING
376:  519       IG1=1
377:            IF(OMEG-OM1)830,840,840
378:  840       IF(OMEG-(OM1+PBIS))841,841,842
379:  842       MIR1=MIR
380:            GOTO 843
381:  841       MIR1=MIR*(OMEG-OM1)/PBIS
382:  843       X=PRL
383:            GOTO 855
384:  830       IF(OMEG-(OM1-PBIS))831,831,832
385:  831       MIR1=MIR
386:            GOTO 833
387:  832       MIR1=MIR*(OM1-OMEG)/PBIS
388:  833       X=PRH
389:  855       CALL MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
```

The above programming sets up the subroutine to calculate which compartment is to have its gas inventory adjusted and by how much. Since this is the first time the subroutine is used, it will be explained here.

For each time step one of the four compartments has gas added to or removed from it. The gas is added at inlet cooling water temperature to the adiabatic cold space. It is removed at the same place it is added. The working space that has received the gas change is noted by setting flag IG3 to 1, 2, 3 or 4. In the previous programming X is set at the high reservoir pressure, PRH (line 388) or the low reservoir pressure, PRL (line 382). The pressure in the working space that is having its pressure adjusted, PX, approaches pressure X exponentially with a time constant MIR1. MIR1 is set by the error in engine speed, OMEG, compared to what is desired (see Figure 4.5). Subroutine MASS is also called from line 440 where the control is from vehicle speed rather than engine speed.

Originally, at this point the mass of gas in the working space was adjusted, thus the name. By experience, it was found that the pressure must be adjusted instead to maintain numerical stability.

```
                SUBROUTINE MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
                DIMENSION P1(4)
                REAL M2,MIR1
                IF(EADEG-45 )860,860,890
        890     IF(EADEG-135 )862,862,856
        856     IF(EADEG-225 )864,864,857
        857     IF(EADEG-315 )858,858,860
      C GAS CHANGE IN WORKING SPACE 1
        858     IG3=1
                PX=X+(P1(1)-X)*EXP(-MIR1*DDT)
                GOTO875
      C GAS CHANGE IN WORKING SPACE 4
        860     IG3=4
                PX=X+(P1(4)-X)*EXP(-MIR1*DDT)
                GOTO875
```

```
871:  C GAS CHANGE IN WORKING SPACE 3
872:  962      IG3=3
873:           PX=X+(P1(3)-X)*EXP(-MIR1*DDT)
874:           GOTO0875
875:  C GAS CHANGE IN WORKING SPACE 2
876:  964      IG3=2
877:           PX=X+(P1(2)-X)*EXP(-MIR1*DDT)
878:  975      RETURN
879:           END
```

The final thing that needs to be done in this branch of the program where the engine is not in gear is to find the new engine speed. This computation was delayed till this point so the old engine speed can be used to adjust engine pressure.

```
390:  C COMPUTE NEW ANGULAR VELOCITY
391:           OMEG=DANG/DDT
392:           GOTO 501
```

For the case where the engine is in gear, a more complicated set of determinations are required. This also is diagrammed in Figure 4.5 (lines 393-449). The first thing is to set the gear ratio (lines 395-420). The equivalent of a clutch is modeled by having the gear ratio change from 0 to the first gear ratio RGE1 in the specified gear change time GCT. The programming specifies a linear change in this ratio. Figure 4.7 shows how the other gear ratios for the second or third gear are applied depending on the vehicle speed. A linear change over the same gear change time is programmed in.

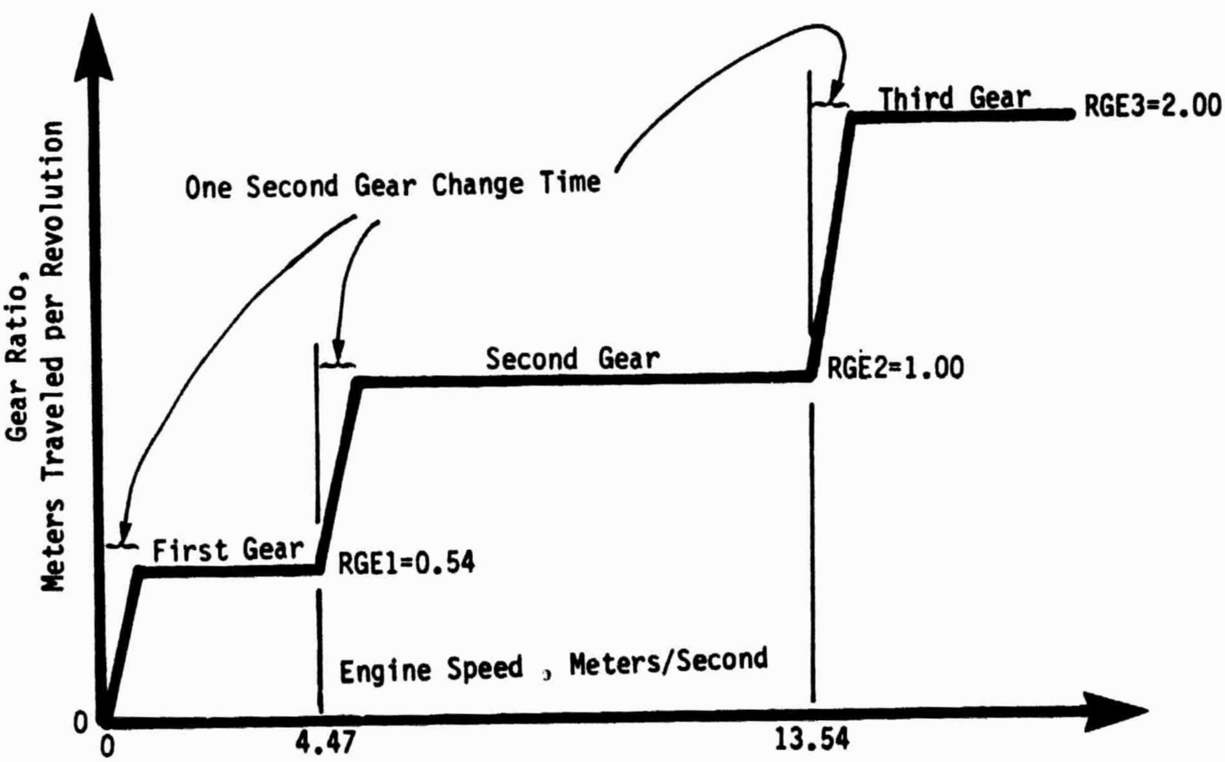

Figure 4.7. Gear Ratio Control.

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OF POOR QUALITY

```
      C ENGINE AND VEHICLE CONTROL WHILE ENGINE IS IN GEAR
520         IG1=2
      C  GEAR CHANGE TIME APPLIED TO ALL GEARS
            IF(NGC)170,171,172
170         IF(TIM-(TI2+GCT))900,901,901
900         RGE=(TIM-TI2)*RGE1/GCT
            GOTO 910
901         IF(SPV1-VSP2)906,905,905
906         RGE=RGE1
            GOTO 910
905         NGC=0
            TIMX=TIM
            GOTO 910
171         IF(TIM-(TIMX+GCT))162,163,163
162         RGE=RGE1+(TIM-TIMX)*(RGE2-RGE1)/GCT
            GOTO 910
163         CONTINUE
            IF(SPV1-VSP3)907,908,908
907         RGE=RGE2
            GOTO 910
908         NGC=1
            TIMX=TIM
            GOTO 910
172         IF(TIM-(TIMX+GCT))166,167,167
166         RGE=RGE2+(RGE3-RGE2)*(TIM-TIMX)/GCT
            GOTO 910
167         RGE=RGE3
            GOTO910
```

Once the gear ratio is determined, the effective vehicle inertia, VIN, is determined. This equation was derived in Section 4.2.6.

```
      C ADDITIONAL EFFECTIVE ENGINE INERTIA DUE TO VEHICLE ATTACHMENT
910         VIN=MIV*(RGE/(2.*PI))**2
```

Next, the scheduled vehicle speed needs to be determined to decide which way the control will go. Resident in the program is a ramp change in speed from zero to the cruising speed followed by a steady cruising speed until the end of the driving cycle.

```
      C FIND SCHEDULED VEHICLE SPEED
            IF(TIM-TI3)912,911,911
912         SPVD=SPM*(TIM-TI2)/TAC
            GOTO 913
911         SPVD=SPM
```

The adjustment of engine pressure to control vehicle speed is standard in automotive Stirling engines. Other things like dead volume control or piston stroke control can be added as options at this point. The control scheme is parallel with that used to control engine speed during idle. (See Figure 4.5.) If the vehicle speed, SPV1 is within the proportional band of PBVS of the scheduled vehicle speed, SPVD, then the valve setting MIR1 is proportional to this error. If the error is beyond this band in either direction, the valve setting is MIR.

Once the valve setting is determined, the switch valve to connect the engine space to either the high pressure reservoir or the low pressure reservoir is set by making X either PRL if gas should come out of the engine or PRH if gas should go into the engine. Once this is determined the subroutine mass is called because two different parts of the program uses it. Subroutine determines which engine compartment gets or gives the gas. It identifies this working space for later use (sets IG3) and determines the new pressure, PX. The subroutine has already been explained in this section.

```
C ADJUST ENGINE PRESSURE TO CONTROL VEHICLE SPEED
913      IF(SPV1-SPVD)930,940,940
940      IF(SPV1-(SPVD+PBVS))941,941,942
942      MIR1=MIR
         GOTO 943
941      MIR1=MIR*(SPV1-SPVD)/PBVS
943      X=PRL
         GOTO 955
930      IF(SPV1-(SPVD-PBVS))931,931,932
931      MIR1=MIR
         GOTO 933
932      MIR1=MIR*(SPVD-SPV1)/PBVS
933      X=PRH
955      CALL MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
```

Next, the rolling friction and air friction are determined. The rolling friction, RF, is in Newtons of retarding force applied to the vehicle. The formula used is from Reference 1. The air friction formula is from the same source. The original rolling resistance formula is:

$$R = (W/65) \quad 1 + (1.4 \times 10^{-3}\, V) + (1.2 \times 10^{-5}\, V^2)$$

where V is vehicle velocity in feet per second and W is vehicle weight in pounds. R is the rolling friction in pounds force.

Units and nomenclature have been converted to:

RF = rolling friction, Newtons
MIV = inertial mass of vehicle, Kg
SPV1 = vehicle speed, meters/second

The air drag specified is for a combined drag coefficient times frontal area of 12 ft^2 = 1.12 m^2 = AFR. The air friction is determined by the formula:

$$AF = \frac{\rho(AFR)}{2} \quad (SPV1)^2$$

where

AF = air friction, Newtons

ρ = air density at 300 K

$$= \frac{29\ g/g\ mol}{22.414\ l/g\ mol} \times \frac{273}{300} \times \frac{1000\ l/m^3}{1000\ g/Kg}$$

$$= 1.1774\ Kg/m^3$$

AFR = frontal area times flow coefficient, m^2

SPV1 = vehicle speed, m/sec

Thus, $$AF = \frac{1.1774}{2}(AFR)\ (SPV1)^2$$

In CNTLA, $$KAR = 0.589\ (AFR)$$

The retarding torque that the rolling and air frictions of the vehicle apply to the engine also depends upon the gear ratio RGE.

```
C TORQUE DUE TO VEHICLE ROLLING FRICTION, AIR FRICTION
          RF=MIV*(0.151+0.000693*SPV1+0.0000195*SPV1**2)
          AF=KAR*SPV1**2
          TQV=(RF+AF)*RGE/(2.*PI)
```

Finally, after all the uses for the old engine speed (angular veolcity) and the old vehicle speed have been applied, new values for both of these are calculated in this part of the program. The engine speed, OMEG, is calculated the same whether it is in the idling or in the in-gear part of the program. However, they cannot be combined because in this part the new vehicle speed, SPV1, depends upon OMEG and also upon RGE, the working gear ratio, which is only defined in this part of the program.

```
C COMPUTE NEW ANGULAR VELOCITY
          OMEG=DANG/DDT
C COMPUTE NEW VEHICLE SPEED
          SPV1=OMEG*RGE/(2.*PI)
```

Now the two parts of the program come together. At this point a check display to the screen is included so that the operator may monitor the solution more accurately than the graphical display does. (See Section 6 for additional details.)

```
C ONE LINE CHECK DISPLAY TO SCREEN
501       WRITE(5,8030)TIM,CFF,REV,OMEG,SPV1,SPVD,RGE,NGC
8030      FORMAT(7E9.3,I3)
```

Whether the engine is stopped, idling or in gear (see Figure 4.4), the cumulative time counter, TIM, is incremented.

```
C INDEX TIME
          TIM=TIM+DDT
C*****END ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
```

This is the end of the explanation of the engine and vehicle control subprogram--part 1. Explanation of the other two parts will be given as they appear in the program.

4.2.7 Burner and Conduction Subprogram

This subprogram along with part of the control program is the only one operative when the engine is stopped. It takes care of controlling the average temperature of the heater tubes at the target temperature and figures heat conduction through the engine to the cooling water. It also computes the transient response of the air preheater.

This subprogram will be explained in the order of calculation. However, before very much in this subprogram will make sense, the nomenclature must be explained.

4.2.7.1 Nodal Organization

Figure 4.8 shows a schematic of the burner and air preheater. Eight metal nodes are chosen since this gives rapid computation and reasonable accuracy (see Appendix A). The metal node temperatures in the air preheater EX(1) to EX(8) must be initialized to ambient or whatever the input file says. (See Section 4.2.2.)

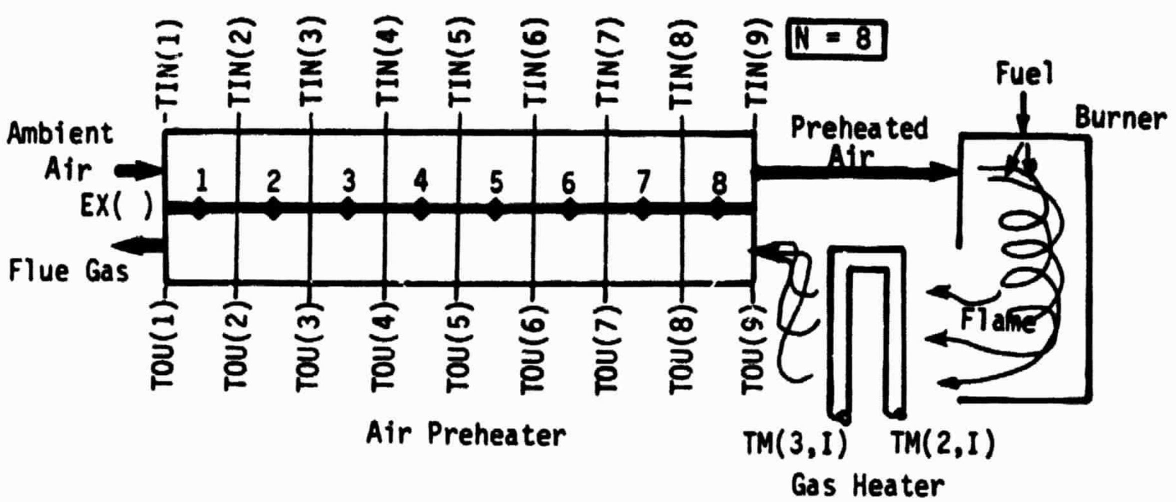


Figure 4.8. Burner and Air Preheater Schematic.

Figure 4.9 shows the metal node nomenclature for the engine needed for burner heating, heat conduction, and engine operation. There are 8 metal nodes defined. Each node has the following properties:

1. a temperature, TM(X,Y), K
2. a location, VM(X,Y) in cm^3 of gas volume from the hot end of the engine to the node point
3. a thermal conductivity, KM(X), from the node point to the next lower one, w/cm K
4. a heat capacity, CM(X), of the material surrounding the node point to half way to the next node point, W/K

In the above list the agruments of the four arrays defined were listed as

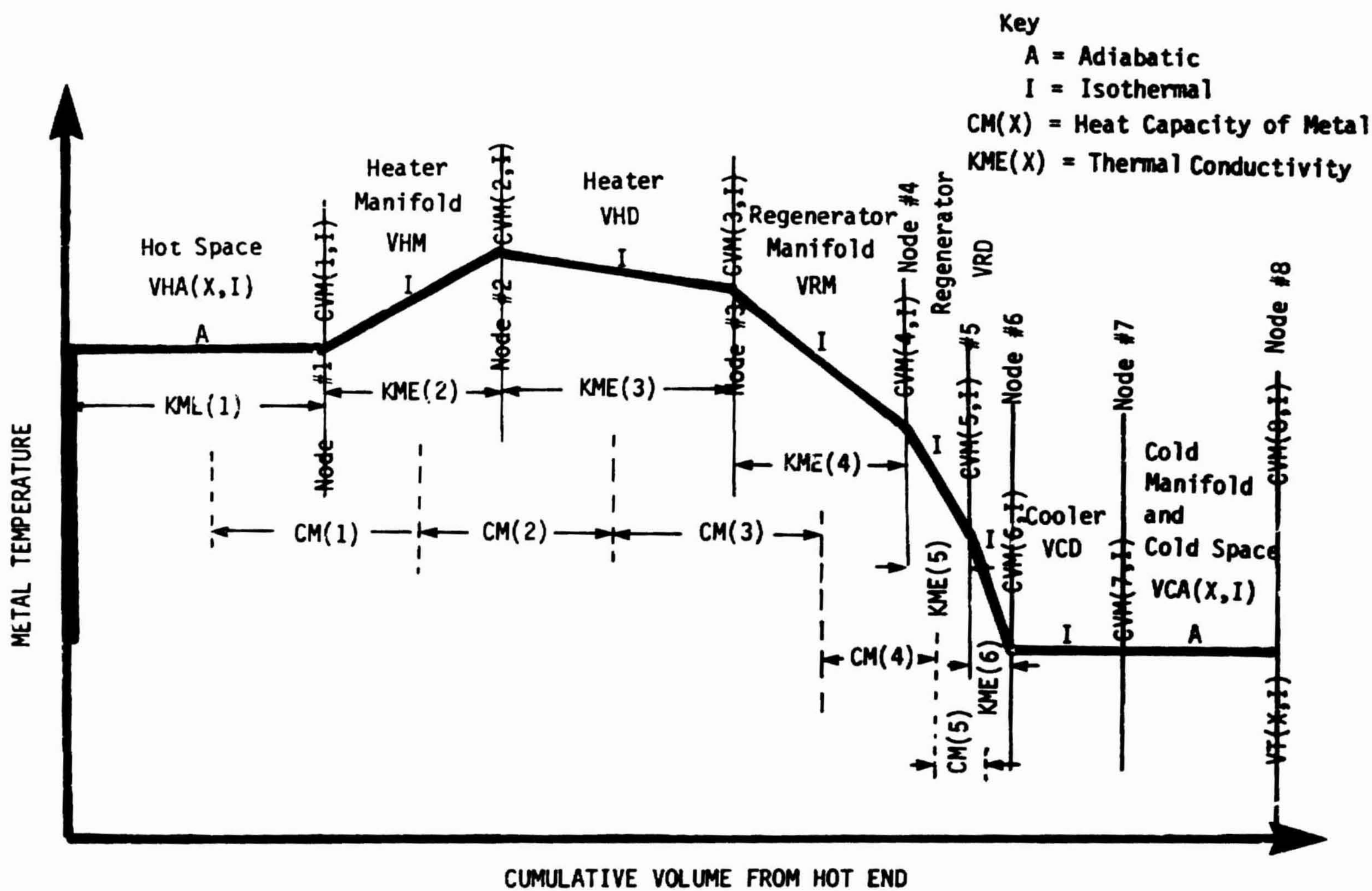


Figure 4.9. Metal and Gas Node Nomenclature.

X and Y. In this case X is the number of metal nodes, 8, and Y is the number of working spaces in the engine, 4.

The gas volume nomenclature for the engine is also shown on Figure 4.9. VHA(X,Y) is the variable hot volume which is assumed to be adiabatic. This is a very good assumption except for a small portion of each cycle. X is for the beginning and end of the time step and Y is for the four cylinders of the engine.

Similarly, VCA(X,Y) is the variable cold volume assumed to be adiabatic.

The constant dead volumes are also identified in Figure 4.9. The gas in these volumes is assumed to attain metal temperature once each cycle. In the engine torque and internal heat transfer subprogram, the heat transferred at each metal node is computed for this equilibration. Afterward the temperatures of the metal nodes are adjusted because of this heat transfer. For well designed engines, the assumption of isothermal spaces in all except for the variable volume spaces is fairly good. The assumption was made to speed up the calculation.

The thermal conductivity attached to metal nodes 1 to 6 is the watts of heat that would pass per ^{o}K of temperature difference. It pertains to the path toward the next lower node number. Note that these thermal conductivities are the same for all cylinders.

The heat capacity attached to metal nodes 1 to 5 determines how fast the temperature of each node changes due to thermal imbalance. All metal node temperatures are adjusted each time step due to external convection and metal conduction.

4.2.7.2 Heater Temperature Control

Now we will proceed with the explanation of the program.

The first thing is the indexing of the metal node temperatures in the air preheater. In the unified printout (see Section 4.2.4), the temperatures of the air (TIN(I)) and the flue gas (TOU(I)) (see Figure 4.8) relate to the original air preheater metal node temperatures, EX(I), rather than the metal node temperatures at the end of the time step EY(I) after heat transfer has taken place. Therefore, this indexing is done at the start of the subprogram.

```
456   C ***** BURNER AND HEAT CONDUCTION SUBPROGRAM
457   C INDEX APH METAL NODE TEMPERATURES
458             DO 8050 I=1,N
459   8050      EX(I)=EY(I)
```

Next, the average temperature for the gas heater metal at the start of the time step is found. According to Figure 4.9 the gas heater has a node on each end of each of the heaters. These temperatures may be different due to different conduction effects or the effect of the gas flowing inside the engine. An average is taken of the temperature of all 8 metal nodes (2 for each working space).

```
460   C FIND AVERAGE HEATER TEMPERATURE FOR CONTROL PURPOSES
461   400      TA=(TM(2,1)+TM(3,1)+TM(2,2)+TM(3,2)+TM(2,3)+TM(3,3)+TM(2,4)
462           1+TM(3,4))/8
```

Then the temperature error is determined and the current fuel flow is determined from it by a proportional control algorithm. Figure 4.10 shows this response scheme. It is a simple proportional band control scheme. The average temperature will always droop a bit below the goal. Better control schemes can be substituted if needed. The fuel usage from the start is [illegible] accumulated. The cumulative fuel usage, FUEL, is initialized on line 675 of CNTLA. Therefore, the value for the cumulative fuel usage is shown at the end of the program.

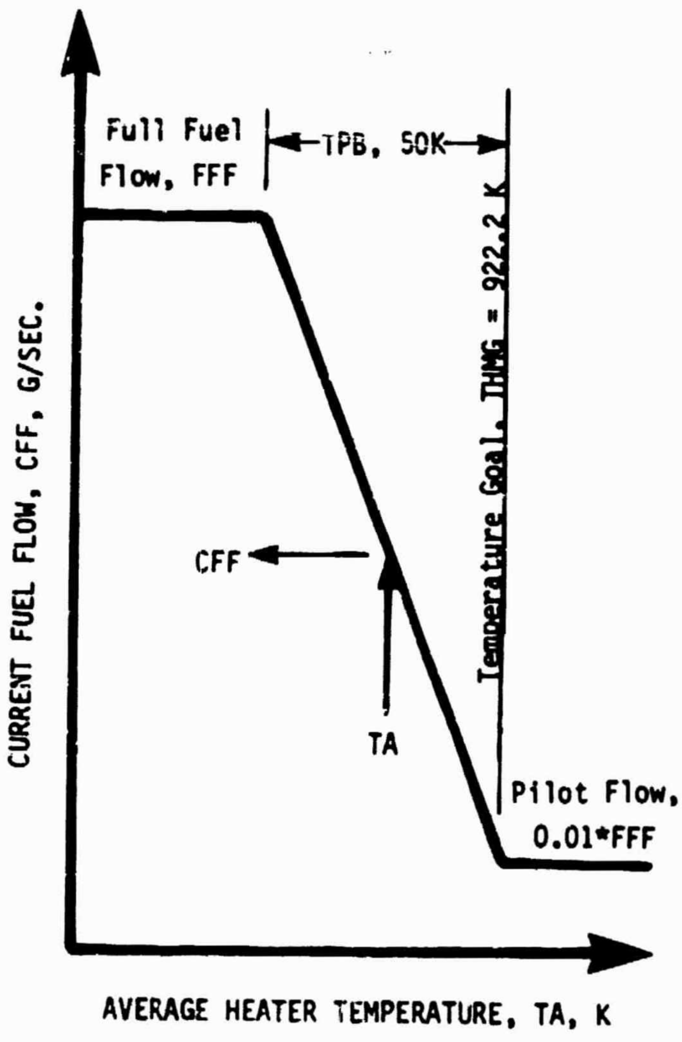


Figure 4.10. Control Scheme for Engine Heaters.

```
      C    TEMPERATURE ERROR (FOR CONTROL)
               TE=THMG-TA
      C    CURRENT FUEL FLOW
               IF(TE)405,405,406
      405      CFF=0.01*FFF
               GOTO409
      406      IF(TE-TPB)408,407,407
      407      CFF=FFF
               GOTO409
      408      CFF=FFF*(TE)/TPB
      409      CONTINUE
               FUEL=FUEL+CFF*DDT
```

4.2.7.3 Heat Transfer Factor Calculation

This next part of the subprogram has to do with calculating heat transfer factors to use in computing heat transfer in the air preheater and to the engine heater tubes. Since this process is complicated and since the results involve correlations that are only good to $\pm 20\%$, it was decided to go through it once at the beginning and then go through it again when the fuel flow has changed more than 20% in either direction. The following shows the if statements that direct the calculation around this part if CFL < CFF < CFH.

```
      C CHANGE HEAT TRANSFER FACTORS IF CFF HAS CHANGED SIGNIFICANTLY
               IF(CFF-CFL) 404,420,420
      404      IF(CFF-CFH) 420,420,403
```

This next part gives the basis for calculating the heat transfer factors for both sides of the air preheater and the gas heater. First, the air flow and the heat capacities must be determined. With the fuel flow specified, the air flow is specified in order to give 10% excess air. The air fuel ratio was based upon normal octane as an average for the fuel actually used. The combustion equation is:

$$C_8H_{18} + 12.5\ O_2 + \underset{\substack{10\% \\ \text{excess}}}{1.25\ O_2} + 51.73\ N_2 \longrightarrow 8\ CO_2 + 9\ H_2O + 1.25\ O_2 + 51.73\ N_2$$

On a one gram mole basis the fuel burned weighs 114.14 g and the air used to burn it weighs 1889.47 g. Therefore, for these assumptions the ratio of air to fuel, RAF = 16.55 as given in the base case. Using this same chemical equation the heat capacity of the flue gas was averaged as follows:

CO_2	8	x	11.94	= 95.52
H_2O	9	x	9.20	= 82.80
O_2	1.25	x	7.94	= 9.93
N_2	51.73	x	7.50	= 386.98
	69.68 g mol			576.22

$$\text{Average flue gas heat capacity} = \frac{576.22}{69.68} = 8.23\ \text{cal/g mol C}$$

The molecular weight of the flue gas is 28.63. Therefore, the heat capacity of the flue gas, CPFG, in the units used in this calculation is 1.20 j/g K. The heat capacity for air, CPA, is 1.03 j/g K. These values are given in the program and can only be changed by revising the data statement (see CNTLB line 32).

Given the fuel flow, the air flow is determined. From the air flow, the mass velocity, GAPH, of air in terms of grams per second of air flowing per cm^2 of flow area is computed. Next the Reynolds number is defined. That is,

$$RE = \frac{DEQ\ (GAPH)}{(\text{viscosity of air})}$$

The equivalent diameter, DEQ, of the rectangular flow area is calculated as 4 times the flow area divided by the wetted perimeter. (See line 669 of CNTLA.) The viscosity of air at 700 K is about 4×10^{-4} g mass/cm sec. The reciprocal of this, 2500, is used to compute the Reynolds number, RE.

```
C     HEAT TRANSFER FACTOR, AIR SIDE
403       GAPH=CFF*RAF/AFAPH
          RE=DEQ*GAPH*2500
          CALL STANTN(RE, STN)
```

From the Reynolds number, the heat transfer coefficient is calculated by means of the correlation shown in Figure 4.11. This correlation is used for both the air and the flue gas side of the air preheater. It is subroutine STANTN.

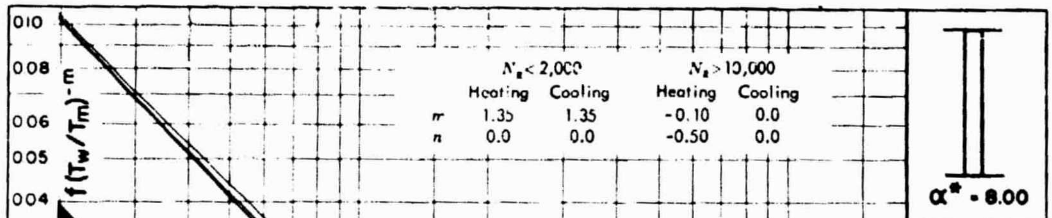


Figure 4.11. Heat Transfer Correlation Used for the Air Preheater (2).

```
      SUBROUTINE STANTN(RE,STN)
      IF(RE-2000)100,100,200
100   STN=EXP(1.6909-0.8767*ALOG(RE))
      GOTO300
200   STN=EXP(-4.0555-0.1903*ALOG(RE))
300   RETURN
      END
```

The output of this correlation is taken as the Stanton number times the Prandtl number to the two-thirds power, the wall temperature factor is ignored. Thus,

$$STN = \frac{h}{(GAPH)\ (CP)}\ (PR^{2/3})$$

At 700 K, the specific heat at constant pressure for air, CP is 1.0752 and the Prandtl number of 0.864. Thus, the heat transfer coefficient is:

$$h = (STN)\ (GAPH)\ (1.19)$$

In modeling the air preheater a number of different mathematical models were tried. It was desired to have something simple but still take into account the transient heat up of the air preheater starting at the hot end. The scheme that was chosen is shown in Figure 4.12. It is assumed taht the air preheater is divided into N segments. For the main program N was chosen as 8. In Appendix A the effect of N on the accuracy of calculation is discussed.

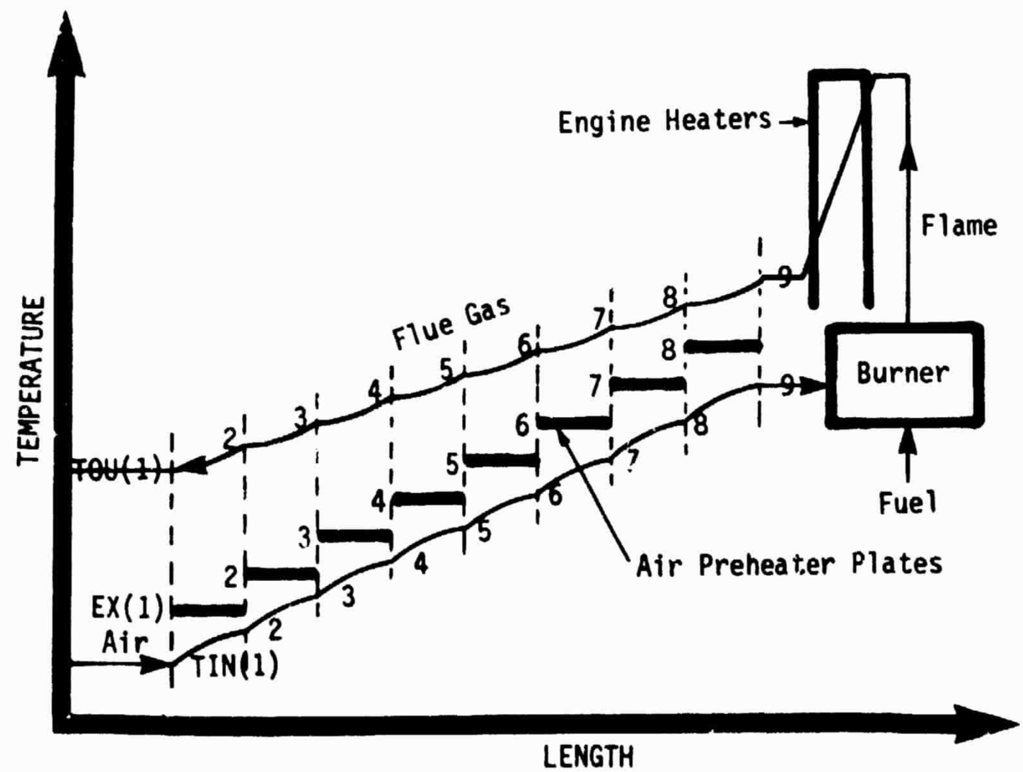


Figure 4.12. Air Preheater Calculation Scheme.

In each segment the air and flue gas are separated by a plate with a constant temperature for that segment. It would be more realistic to assume a constant temperature gradient but the mathematical formulation was too complicated and would involve an iterative solution at each time step. The method chosen will be sufficiently accurate except at very low flows. Note that for each node both the air and the flue gas temperature approach the temperature of the air preheater plate. Both of these processes involve heat transfer to or from the plate. Then there is the process of conduction from one metal node to the next. In CNTLB the temperature of each metal node, EX(N), is changed after both air and flue gas heat transfers are calculated. In WARM (Appendix A) metal temperatures were changed twice and heat conduction along the metal was ignored.

The calculation starts by setting the metal node temperatures, EX(1) to EX(8). The inlet air temperature, TIN(1) is taken as the ambient air temperature. TIN(2) is calculated from TIN(1) as will be shown hereafter. TIN(3) is calculated from TIN(2) and so on up the stairs to TIN(9), the temperature of the air leaving the air preheater. This preheated air burns with the fuel to produce a gas with a temperature FLAME. It exchanges heat with four sets of engine heaters which may have different temperatures due to the internal workings of each part of the engine. Each engine section has a metal node at both ends of the engine heater. It is assumed that the same heat transfer coefficient applies to all heater nodes. The flue gas leaving the engine heaters has cooled and may be at different temperatures. It is averaged to become TOU(9). The flue gas is now cooled down along the stairstep air preheater in the same way the air heats up. Finally, the temperatures of the air preheater metal is adjusted due to air and flue gas heat transfer and metal conduction. Also, the temperatures in the engine are adjusted due to metal conduction. In another part of the program which is active when the engine rotates the engine metal node temperature will be further adjusted due to heat transfer with the working gas. In all these calculations the time step must be small enough so that the metal node temperatures do not change very much each increment. If they did, calculational instabilities would build up and destroy the simulation.

For the first increment in the heat exchanger, the heat transferred from the metal to the air, H, can be expressed two different ways.

$$\underset{\substack{\text{Heat}\\\text{Transfer}\\\text{watts}}}{H} = \underset{\substack{\text{Heat}\\\text{Capacity}\\\text{j/g K}}}{CPA} * \underset{\substack{\text{Air Flow}\\\text{g/sec}}}{\overbrace{CFF * RAF}} * \underset{\substack{\text{Temperature Rise}\\\text{K}}}{\overbrace{(TIN(2) - TIN(1))}}$$

and

$$H = h \cdot A_h * \frac{(EX(1) - TIN(1)) - (EX(1) - TIN(2))}{\ln\left\{\frac{EX(1) - TIN(1)}{EX(1) - TIN(2)}\right\}}$$

where $h = STN * GAPH * 1.19$

$$A_h = \underset{\text{length}}{LAPH} * \underset{\text{width}}{WAPH} * \underset{\text{number one way}}{NAPH} * \underset{\text{2 sides}}{2}/\underset{\text{number of nodes}}{NO}$$

When the above two equations are combined and solved for TIN(2), the result is:

$$TIN(2) = EX(1) - \frac{EX(1) - TIN(1)}{\exp(X)} \qquad (1$$

where $X = UXX * STN * GAPH * 1.19/CFF$

$$UXX = \frac{LAPH * WAPH * 2 * NAPH}{NO * RAF * CPA}$$

In evaluating Equation 1, it is easily possible for X to be large enough to overflow the number size limit of a computer. For the Altos Z 80 based microcomputer used to develop this program, exp(32) was about as large as the computer would go without giving an overflow error. Therefore, if $X > 32$, it is made equal to 32. Therefore, the heat transfer factor is:

$$XY = \exp(X)$$

and the final equation to find the air temperatures in succession is:

$$TIN(2) = EX(1) - (EX(1) - TIN(1))/XY$$

Similarly, TIN(3) is calculated from TIN(2) and so on to TIN(9).

All of the above is necessary to explain the programming lines below, to find the heat transfer factor for the air side of the air preheater. The constant UXX is evaluated on line 673 in CNTLA and brought over through the data file.

```
          X=UXX*STN*GAPH*1.19/CFF
          IF(X.GT.32.)X=32.
          XY=EXP(X)
```

The heat transfer factor for the flue gas side of the air preheater is calculated in the same way as the air side. The flow rate is greater and the heat capacity is greater. A quantity UXY analogous to UXX is brought over from CNTLA and used here.

```
C     HEAT TRANSFER FACTOR, FLUE GAS SIDE
          GAPH=CFF*(RA1)/AFAPH
          RE=DEQ*GAPH*2500.
          CALL STANTN(RE,STN)
          X=STN*GAPH*1.19*UXY/CFF
          IF(X.GT.32.) X=32
          XZ=EXP(X)
```

Next, the heat transfer factor, XH, for the flame heating the heater tubes must be calculated.

Direct flame heated Stirling engines always have the outside heat transfer coefficient controlling.

The equation and the values assumed to be valid for this case were taken from Table 4.2.

Table 4.2

EQUATION PARAMETERS USED FOR

HEAT TRANSFER TO GAS HEATER (3)

$h_m D_o / k_f = b_2 (D_o G_{max} / \mu_f)^n;\ t_f = t_s - (t_s - t)_m / 2$

$x_L = \frac{s_L}{D_o}$	$x_T = 1.25$		$x_T = 1.5$		$x_T = 2$		$x_T = 3$	
	b_2	n	b_2	n	b_2	n	b_2	n
Staggered:								
0.600	.....	.....	...				0.213	0.636
0.900	.....	.....	.....	...	0.446	0.571	0.401	0.581
1.000	....	....	0.497	0.558				
1.125	.....				0.478	0.565	0.518	0.569
1.250	0.518	0.556	0.505	0.554	0.519	0.556	0.522	0.562
1.500	0.451	0.568	0.460	0.562	0.452	0.568	0.488	0.568
2.000	0.404	0.572	0.416	0.568	0.482	0.556	0.449	0.570
3.000	$\boxed{0.310}$	$\boxed{0.592}$	0.356	0.580	0.440	0.562	0.421	0.574
In line:								
1.250	0.348	0.592	0.275	0.608	0.100	0.704	0.0633	0.752
1.500	0.367	0.586	0.250	0.620	0.101	0.702	0.0678	0.744
2.000	0.418	0.570	0.299	0.602	0.229	0.632	0.198	0.648
3.000	0.290	0.601	0.357	0.584	0.374	0.581	0.286	0.608

$x_L = s_L/D_o;\ x_T = s_T/D_o.$

In the 4L23 engine there is one row of heater tubes. In the P-40 engine there are two rows widely separated. Assume that the pitch to diameter ratio is 1.25. That is, each tube is separated from the next by a space $\frac{1}{4}$ the outside diameter of the tube. Assume that the transverse pitch is large, say, 3 times the outside diameter. Also, assume that the heated length includes the front and back row and negligible for the bend. Thus, the gas heater minimum flow area is:

$$AMF = \frac{DOH}{4} * \frac{LHH}{2} * NTH * 4$$

cylinders per engine

$$= DOH * LHH * NTH/2$$

Therefore, the maximum mass velocity is:

$$GMAX = CFF * (RA1)/AMF$$

At 1000 K the viscosity of air is:

$$\mu_f \cong 6 \times 10^{-4} \text{ g/cm sec}$$

and the thermal conductivity is:

$$k_f \cong 7 \times 10^{-4} \text{ w/cm K}$$

Therefore, by substituting into the equation from Table 4.2 and simplifying, the heat transfer coefficient is found to be:

$$UH = \frac{DOH * CFF * RA1}{AMF * 0.0006} ** 0.592 * 0.00022/DOH$$

It is also not necessary to evaluate the heat transfer coefficient every time step since it changes little so it is grouped with the evaluation of the heat transfer coefficient for the air side and is only re-evaluated when the flow changes appreciably.

Each part of the engine may have a different heater temperature depending upon what is going on inside. However, it is assumed that $\frac{1}{4}$ of the flame passes through each of the four engine sections. For each section the heat transfer can be expressed two ways (see Figure 4.13):

By temperature change:

$$H = \frac{CFF}{4} * RA1 * CPFG * (FLAME - T3A(Y))$$

And by heat transfer:

Let

$$X = (TM(2,Y) + TM(3,Y))/2$$

$$H = UH * AH * \frac{(FLAME - X) - (T3A(Y) - X)}{\ln\left(\frac{FLAME - X}{T3A(Y) - X}\right)}$$

Combining the above two equations gives:

$$T3A(Y) = X + (FLAME - X)/XH$$

where

$$XH = \exp\left(\frac{UH * AH * 4}{CFF * CZ}\right)$$

$$AH = PI * DOH * LHH * NTH$$

$$CZ = CPFG * RA1$$

If the argument of the exponential is greater than 32 it is made 32 to prevent overflow in the computer.

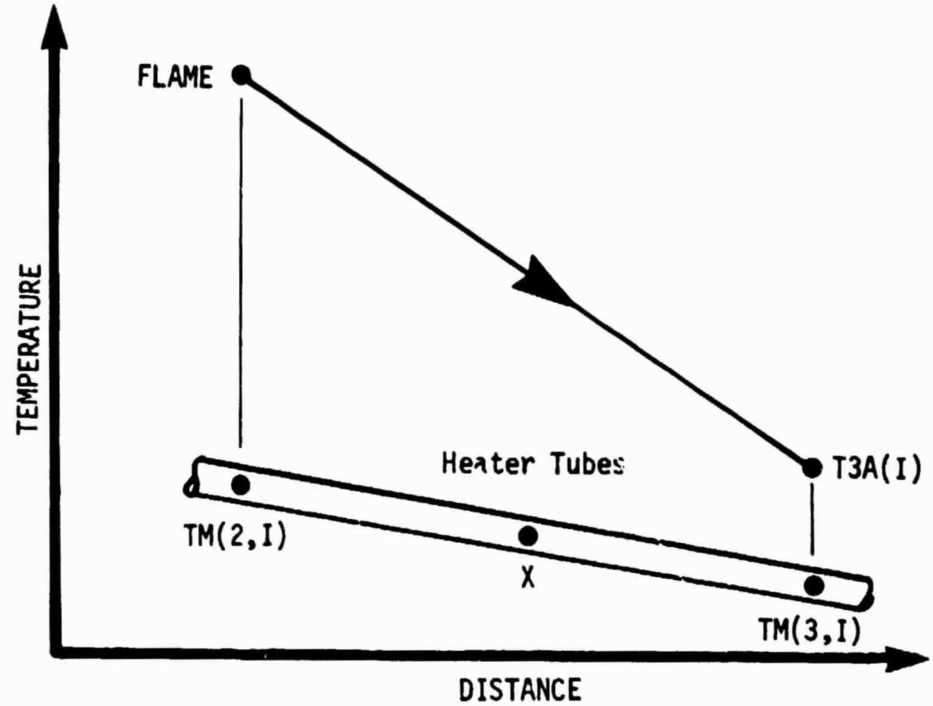


Figure 4.13. Gas Heater Heat Transfer Scheme.

All the above explanation is necessary to show how the heat transfer factor, XH, is computed and used. The programming is:

```
C    HEAT TRANSFER FACTOR, GAS HEATER
        UH=(DOH*CFF*RA1/AMF/.0006)**0.592*0.00022/DOH
        X=-4.*UH*AH/(CFF*C7)
        IF(X.GT.72.) X=72.
        XH=EXP(X)
```

Every time the heat transfer factors are calculated the flow bounds must be recalculated.

```
C    RESET FLOW BOUNDS
        CFH=1.2*CFF
        CFL=0.8*CFF
```

4.2.7.4 Air Side Temperature Calculation

Now that the heat transfer factors are calculated (if they have had to be), the temperatures through the air and flue gas circuit can be quickly determined. In this calculation it is assumed that the thermal lag due to heat capacity of the metal parts is so important that the added complication of figuring transit times for the gas around the circuit is not necessary. Therefore, steady state temperatures are calculated for the gas side. Cal culation starts with ambient air at the inlet to the air preheater and works

around the circuit. First, the air temperatures in the preheater are calculated sequentially as has already been explained.

```
500   C CALCULATE APH AIR TEMPERAUPES
501   420      DO 427 I=1,N
502   427      TIN(I+1)=EX(I)-(EX(I)-TIN(I))/XY
```

2. Burner Calculation

Next, the preheated air enters the burner. The temperature rise is given by the equation

$$LHV * 1000 * CFF = CFF * (RAF + 1) * CPFG * DT2$$

heat supplied by fuel combustion, watts	heat absorbed by flue gas temperature rise, watts

which reduces to:

$$DT2 = \frac{LHV * 1000}{(CPFG) * (RAF + 1)}$$

LHV = lower heating value of fuel = 46.432 Kj/g
= 20,000 BTU/lb

CPFG = heat capacity of flue gas = 1.20 j/g K

RAF = ratio of air flow to fuel flow, j/g

(RAF + 1) = ratio of flue gas flow to fuel flow

CFF = current fuel flow, g/sec

DT2 = temperature rise in flue gas temperature (neglecting disassociation)

Note that DT2, in the simple way it is calculated here, neglecting disassociation and heat loss through burner insulation, is not dependent on flue flow. DT2 comes from CNTLA, line 671.

```
503   C   FIND FLAME TEMPERATURE
504            FLAME=TIN(N+1)+DT2
```

4.2.7.6 Heat Transfer to Gas Heaters

Next, the four effluents from the heaters are calculated as has been explained.

```
505   C   DETERMINE OUTLET FLUE GAS TEMP. FROM HEATERS
506            DO 437 I=1,4
507            X=(TM(2,I)+TM(3,I))/2.
508   437      T3A(I)=X+(FLAME-X)/XH
```

The flue gas temperatures are averaged and the one outlet temperature, TOU(N+1), is obtained.

```
509   C   AVERAGE FLUE GAS TEMPERATURES
510            TOU(N+1)=(T3A(1)+T3A(2)+T3A(3)+T3A(4))/4
```

4.2.7.7 Flue Gas Side Temperature Calculation

Finally, the flue gas temperatures down the stairsteps of the air preheater are calculated as has been explained.

```
C     EXIT FLUE GAS TEMPERATURES THROUGH AIR PREHEATER
      DO446 I=1,N
      K=N-I+1
446   TOU(K)=EX(K)+(TOU(K+1)-EX(K))/XZ
```

4.2.7.8 Metal Temperature Adjustment in Air Preheater

Next, the metal node temperatures in the air preheater must be adjusted for heat transfer and conduction. For the first node the heat lost, in joules, to the air is:

$$X = CFF * RAF * CPA * (TIN(2) - TIN(1)) * DT$$

The heat gained from the flue gas is:

$$Y = CFF * RA1 * CPFG * (TOU(2) - TOU(1)) * DT$$

The heat gained by metallic conduction is:

$$ZZ = KM * (TMAPH * NAPH * NAPH * 2) * \frac{(EX(2) - EX(1))}{(LAPH/NO)} * DT$$

$$ZZ = KAPH * (EX(2) - EX(1)) * DT$$

The heat capacity of most metals on a volume basis is about the same, 500 j/cm^3K. Thus, the heat capacity in each metal node is:

$$CMAPH = \frac{LAPH * WAPH * 2 * NAPH * TMAPH * 5.00}{NO}$$

Therefore, a heat balance on the first metal node is:

$$CMAPH(EY(1) - EX(1)) = ZZ + Y - X$$

Therefore, the metal node temperature at the end of the time step is:

$$EY(1) = EX(1) + (ZZ + Y - X)/CMAPH$$

This derivation is different for the middle nodes and the other end nodes but the concept is the same. It is assumed that the air preheater metal is not connected to any other heat source or heat sink except the gases flowing through it. Based upon the above explanation the following programming calculates the new air preheater metal node temperatures.

```
      C  CHANGE APH METAL NODE TEMP. DUE TO CONVECTION AND CONDUCTION
               DO 430 I=1,N
               X=CFF*RAF*CPA*(TIN(I+1)-TIN(I))*DDT
               Y=CFF*RA1*CPFG*(TOU(I+1)-TOU(I))*DDT
               IF(I-1)448,448,450
      450      IF(I-8)449,451,451
      448      ZZ=KAPH*(EX(I+1)-EX(I))*DDT
               GOTO 452
      449      ZZ=KAPH*(EX(I+1)-2.*EX(I)+EX(I-1))*DDT
               GOTO 452
      451      ZZ=-KAPH*(EX(I)-EX(I-1))*DDT
      452      CONTINUE
      430      EY(I)=EX(I)+(ZZ+Y-X)/CMAPH
```

4.2.7.9 Metal Temperature Adjustment in the Engine

Five metal nodes in each of the four parts of the engine float in temperature. They receive and give up heat by conduction and by being heated by the heater all the time. This part will now be explained.

Each node as shown in Figure 4.9 is a special case but the formulation for calculating the same node in the four parts of the engine is the same. The calculation for each engine metal node will now be explained.

Metal Node 1 is the metal around the hot space, half the way to the water cooled portion of the engine cylinder. The thermal conductance to the cooling jacket is:

$$KME(1) = \frac{KM * PI * DCY * (TCY + THC)}{HCL}$$

KME(1) to KME(6) are brought over from CNTLA.

The thermal conductance from the heater is:

$$KME(2) = \frac{KM * PI * DIHM * WTHM * NTHM}{LHM}$$

The heat capacity of metal node 1 also involves the same specific heat capacity of 5.00 j/cm^{3}K. This heat capacity in j/K degree change is computed as follows:

The metal volume of the end caps is:

$$X = PI4 * DCY ** 2 * (THH + TCHC)$$

The metal volume of the cylinder wall belonging to the node is:

$$Y = PI * DCY * (TCY + THC) * HCL/2$$

The metal volume of the heater manifold belonging to the node is:

ZZ = PI * DIHM * WTHM * NTHM * LHM/2

Thus the nodal heat capacity is:

CM(1) = (X + Y + ZZ) * 5.00

CM(1) to CM(5) is brought over from CNTLA.

In the calculation the metal node temperatures will be changed once due to flame heating and metal conduction and then later in the program due to internal heat transfer. One must have two sets of metal node temperatures. Each temperature figures in several equations. It would not do to mix new and old temperatures in the calculations. In metal node 1, for the time step DDT, the heat lost to the cooling jacket is:

A = KME(1) * (TM(1,I) - TWI) * DDT

The heat gained through the heater manifold is:

B = KME(2) * (TM(2,I) - TM(1,I) * DDT

Thus, a heat balance of metal node 1 gives:

CM(1) * (TM1(1,I) - TM(1,I) - B - A

Therefore, the new metal temperature due to one time step's worth of conduction is:

$$TM1(1,I) = TM(1,I) + \frac{B - A}{CM(1)}$$

Note that the I represents the four cylinders which will have different internal heat transfers.

```
[illegible]  C    CHANGE ENGINE METAL NODE TEMPS  DUE TO COND.  AND OUTSIDE CONV
569               DO 499 I=1,4
570               A=KME(1)*(TM(1,I)-TWI)*DDT
571               B=KME(2)*(TM(2,I)-TM(1,I))*DDT
572               TM1(1,I)=TM(1,I)+(B-A)/CM(1)
```

Metal node 2 is centered at the junction between the heater manifold and the heater. It includes half the heater manifold and half the heater. Pertaining to it are thermal conductance KME(2), already defined, and KME(3) between the two ends of the heater. Thus:

KME(3) = KM * PI4 * (DOH ** 2 - DIH ** 2) * NTH/LHH

The heat capacity of metal node 2 involves the other half of the heater manifold metal volume, already calculated as Z, and half of the heater metal volume which is:

X = PI4 * (DOH ** 2 - DIH ** 2) * NTH * LHH/2

Thus, the nodal heat capacity is:

CM(2) = (Z + X) * 5.00

In metal node 2 the heat loss in joules for the time step DDT to node is already calculated as B. The heat loss to metal node 3 by conduction is:

$$A = KME(3) * (TM(2,I) - TM(3,I)) * DDT$$

The heat gain due to flame heating is:

$$C = \left[\frac{CFF}{4} * RA1 * CPFG * (FLAME - T3A(I))\right] * DDT/2$$

since half of the heat from the flame is assumed to go to node 2 and half to node 3. Therefore, by a heat balance

$$CM(2) * (TM1(2,I) - TM(2,I)) = C - A - B$$

Thus, the new temperature on metal node 2 after one time step's worth of conduction and external heat transfer is:

$$TM1(w,I) = TM(2,I) + \frac{C - A - B}{CM(2)}$$

```
      A=KME(3)*(TM(2,I)-TM(3,I))*DDT
      C=(CFF/4.*RA1*CPFG*(FLAME-T3A(I)))*DDT/2
      TM1(2,I)=TM(2,I)+(C-A-B)/CM(2)
```

Metal node 3 is centered at the junction between the heater and the regenerator manifold. It includes half the heater and half the regenerator manifold. Pertaining to it are thermal conductance KME(3) already defined and KME(4) along the regenerator manifold. Thus:

$$KME(4) = XM * PI * DIRM * WTRM * NTRM/LRM$$

The heat capacity of this metal node involves the other half of the heater metal volume already calculated as X and half of the regenerator manifold metal volume. Thus:

$$Y = PI * DIRM * WTRM * NTRM * LRM/2$$

Thus the nodal heat capacity is:

$$CM(3) = (X + Y) * 5.00$$

In this node the heat gain by conduction from metal node 2 is already calculated as A. The heat gain due to flame heating is already calculated as C. The heat loss by conduction to metal node 4 is:

$$B = KME(4) * (TM(3,I) - TM(4,I)) * DDT$$

Therefore, by a heat balance

$$CM(3) * (TM1(E,I) - TM(3,I) = A + C - B$$

Thus, the new temperature of metal node 3 after one time step's worth of conduction and external heat transfer is:

$$TM1(3,I) = TM(3,I) + \frac{A + C - B}{CM(3)}$$

```
576      B=KME(4)*(TM(3,I)-TM(4,I))*DDT
577      TM1(3,I)=TM(3,I)+(A+C-B)/CM(3)
```

Metal node 4 is centered at the hot end of the regenerators attached to each cylinder. It includes the heads on the regenerators, half the regenerator manifolds, and one quarter of the regenerator matrix and one quarter of the regenerator wall. Pertaining to it are thermal conductance KME(4), already defined,as well as KME(5) between the hot end and the middle of the regenerator. Thus:

$$KME(5) = KM * PI * DR * RWT * NR/(LR/2)$$

$$+ KMX * PI4 * DR ** 2 * NR/(LR/2)$$

The heat capacity of the metal node involves the other half of the regenerator manifold volume already calculated as Y. The volume of the regenerator heads is:

$$X = PI4 * (DR + RWT) ** 2 * TRH * NR$$

and $\frac{1}{4}$ the metal volume of the regenerator and surrounding cylinder wall. Thus:

$$ZZ = PI * DR * RWT * LR/4 + PI4 *DR ** 2 * LR/4 * FF$$

Thus, the nodal heat capacity is:

$$CM(4) = (Y + X + ZZ) * 5.00$$

In this node the heat gain by conduction from node 3 is already calculated as B. The heat loss by conduction to the middle of the regenerator is:

$$A = KME(5) * (TM(4,I) - TM(5,I) * DDT$$

There is no external heat transfer in this node. By heat balance

$$CM(4) * (TM1(4,I) - TM(4,I) = B - A$$

Thus, the new temperature of metal node 4 after one time step's worth of conduction is:

$$TM1(4,I)= TM(4,I) + \frac{B - A}{CM(4)}$$

```
578      A=KME(5)*(TM(4,I)-TM(5,I))*DDT
579      TM1(4,I)=TM(4,I)+(B-A)/CM(4)
```

Metal node 5 is centered at the center of the regenerator and includes the middle half of the regenerator. Pertaining to it are thermal conductances KME(5) between the hot end and the middle of the regenerator and KME(6) between the middle and the cold end of the regenerator. Since dependence of thermal conductivity on temperature is being ignored, KME(6) = KME(5).

The heat capacity involves half the metal volume of the regenerator and surrounding cylinder wall. Thus, the heat capacity for this node is:

$$CM(5) = 2 * ZZ * 5.00$$

The heat gain from the hot part of the regenerator is already calculated, A. The heat loss to the cold part of the regenerator is:

$$B = KME(6) * (TM(5,Y) - TM(6,Y)) * DDT$$

By heat balance

$$CM(5) * (TM1(5,Y) - TM(5,Y)) = A - B$$

Thus, the new temperature of metal node 5 after one time step's worth of conduction is:

$$TM1\ (5,Y) = TM(5,Y) + \frac{A - B}{CM(5)}$$

```
          B=KME(6)*(TM(5,I)-TM(6,I))*DDT
    489   TM1(5,I)=TM(5,I)+(A-B)/CM(5)
```

The value TM(6,Y) is always equal to TMI.

4.2.7.10 Index Metal Temperatures

At this point the new engine metal node temperatures, TM1(X,I) are transferred to the old metal node temperature TM(X,I) which is displayed. When the engine rotates, the metal temperatures TM(X,I) will be changed once again. However, this time new and old metal temperatures will not be needed.

```
C  INDEX OF TM1(K,I) TO TM(K,I)
          DO 422 K=1,5
          DO 426 I=1,4
          TM(K,I)=TM1(K,I)
    426   CONTINUE
    422   CONTINUE
```

4.2.7.11 Average Temperatures

Finally, average metal temperatures between the metal node points must be calculated. These temperatures also become the gas node temperatures for the isothermal section of the engine.

```
C  AVERAGE METAL TEMPERATURES FOR ISOTHERMAL NODES
          DO 751 I=1,4
          DO 752 K=2,6
    752   TMA(K,I)=(TM(K,I)+TM(K-1,I))/2
          TMA(7,I)=TM(6,I)
    751   CONTINUE
C***** END OF BURNER AND HEAT CONDUCTION SUBPROGRAM
```

4.2.8 Engine and Vehicle Control Subprogram (EVSC) Part 2

Part 2 does one thing. It tests flag IG1. If the engine should be stopped, it returns to the unified read out (see Section 4.2.4). If it should be

going, it goes on to the next section.

```
C*****CONTROL PROGRAM PART 2
C TEST FLAG TO DECIDE WHETHER TO GO ON TO NEXT SUBPROGRAM
        IF(IG1-1)401,425,425
```

4.2.9 Engine Torque and Internal Heat Transfer Subprogram

The engine calculation subprogram calculates the torque generated by the engine for the conditions of temperature and pressure in each of the four engine spaces and for the engine speed at the time. In order to speed up the calculations, the following simplifying assumptions are made:

1. The gas pressure in each engine space is uniform.
2. Internal heat transfer between the gas and the solid is perfect in the heater manifold, heater tubes, regenerator manifold, regenerator and cooler.
3. There is no heat transfer between the gas and the solid in the hot space and in the cold space and in the cold manifold.
4. The regenerator metal temperature is initially assumed to be linear, but during operation the midpoint metal temperature is adjusted so that the net heat transfer to the regenerator (metal node 5) is zero.
5. The metal in both the heater manifold and the regenerator manifold is assumed to have linear temperature gradients.

The calculations in this subprogram proceed in the following steps. Each will be explained as needed followed by the applicable program segment.

Step 1 - Calculate New Engine Volumes

The engine volumes for each compartment depends upon the engine angle EARAD. This angle is determined from the last engine position and the angle increment, DANG, derived from a torque balance and assessment of acceleration. This step gives all the variable volumes for the four working spaces and the total volumes for each working space. Figure 4.14 shows the spacing between the cold end of each cylinder and the cold end of each piston for somewhat more than one cycle. Note that at 0 degrees, cylinder 1 (X1) has the power piston at the cold end. Then at 90° engine angle, cylinder 4 has minimum cold space. At 180° cylinder 3 has minimum cold space. At 270° cylinder 2 has minimum cold volume.

In the Siemens arrangement which is used in the 4L23 engine as well as all the United Stirling machines, the hot end of one cylinder is connected to the cold end of the next through the heater, regenerator and cooler. Figure 4.14 and Table 4.3 shows how they are connected.

Daniele and Lorenzo (4) have indicated that gas can only be added to or removed from each working space through a timing slot in the drive rod. For the purpose of this program it was assumed that these timing slots would be full open 45° before and 45° after bottom dead center. This is the reason for the addition, removal schedule given in the explanation of the engine and vehicle control subprogram.

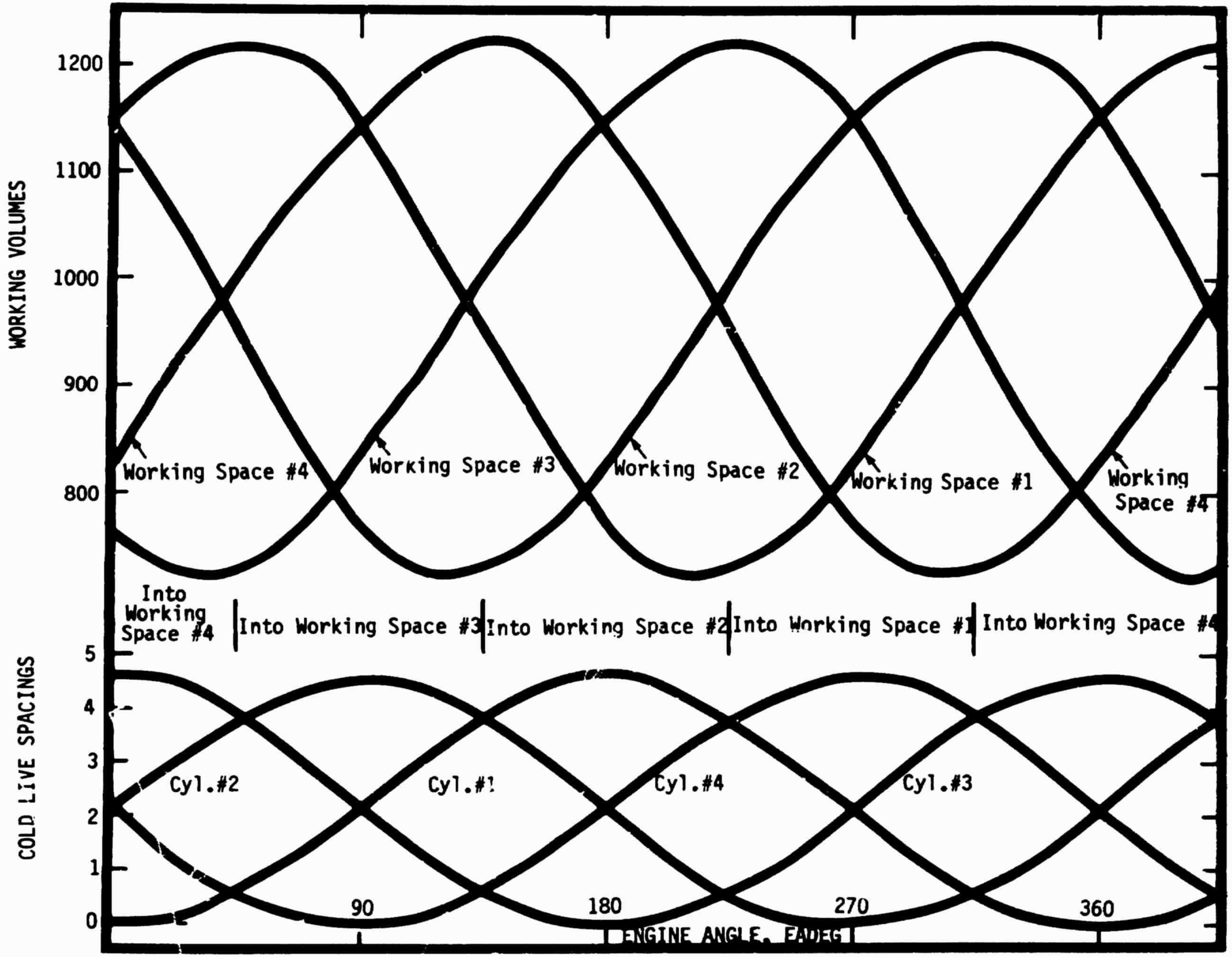


Figure 4.14. Volumes and Spacings in Engine.

Table 4.3

ENGINE SPACE NOMENCLATURE

Working Space Number	Hot Space Cylinder Number	Cold Space Cylinder Number
1	1	2
2	2	3
3	3	4
4	4	1

The quantities X1 to X4 graphed in Figure 4.14 are calculated from the formula for a crank operated piston (5). From these the variable volumes in the hot space, VHA(X,Y), and in the cold space, VCA(X,Y) are calculated.

```
C*****ENGINE TORQUE AND INTERNAL HEAT TRANSFER SUBPROGRAM
C  STEP 1--CALCULATE NEW ENGINE VOLUMES
425       X1=SQRT(XA-(RC*SIN(EARAD))**2)-RC*COS(EARAD)-XB
          X2=SQRT(XA-(RC*SIN(EARAD+PI2))**2)-RC*COS(EARAD+PI2)-XB
          X3=SQRT(XA-(RC*SIN(EARAD+PI))**2)-RC*COS(EARAD+PI)-XB
          X4=SQRT(XA-(RC*SIN(EARAD+PI32))**2)-RC*COS(EARAD+PI32)-XB
          VHA(2,1)=ACY*(RC2-X1)+VHDX
          VCA(2,1)=BCY*X2+VCDA
          VHA(2,2)=ACY*(RC2-X2)+VHDX
          VCA(2,2)=BCY*X3+VCDA
          VHA(2,3)=ACY*(RC2-X3)+VHDX
          VCA(2,3)=BCY*X4+VCDA
          VHA(2,4)=ACY*(RC2-X4)+VHDX
          VCA(2,4)=BCY*X1+VCDA
          DO 250 I=1,4
          VT(2,I)=VTD+VHA(2,I)+VCA(2,I)
250       CONTINUE
```

Finally, in Step 1 the cumulative volumes are calculated from the variable and fixed volumes. Each cumulative volume is calculated from the hot end of the engine to a particular point in the engine. (See the nomenclature.) Volumes recorded this way are needed later in the calculation.

```
C CALCULATE NEW ENGINE SPACE CUMUMATIVE VOLUMES
          DO 982 I=1,4
          CVM(1,I)=VHA(2,I)
          CVM(2,I)=CVM(1,I)+VHM
          CVM(3,I)=CVM(2,I)+VHD
          CVM(4,I)=CVM(3,I)+VRM
          CVM(5,I)=CVM(4,I)+VRD/2
          CVM(6,I)=CVM(5,I)+VRD/2
          CVM(7,I)=CVM(6,I)+VCD
          CVM(8,I)=VT(2,I)
982       CONTINUE
```

Step 2 - Calculate Effect of Control

In this version of the program the control method is by adding or removing gas. The control subprogram computed a new pressure, PX, for a particular working space, IG3. (See lines 856-879.) Step 2 calculates the effect of this action on the engine torque and heat transfer.

The first thing is to calculate Y, the ratio of the volume now occupied by the gas originally in the working space for which pressure has been adjusted. This is done assuming the total volume is adiabatic. Next X, the volume of gas added, is calculated. If X is negative, gas has been removed.

```
586   C STEP 2--CHANGE IN GAS VOLUMES, TEMPERATURES AND GAS NODE INVENTORIES
587   C     OF WORKING SPACE THAT CAN HAVE ITS GAS INVENTORY ADJUSTED.  X=
588   C VOLUME OF GAS ADDED(+) OR REMOVED(-) AT CURRENT PRESSURE AND TEMP.
589   C     FOR THAT WORKING SPACE
590             Y=(P1(IG3)/PX)**KR
591             X=VT(1,IG3)*(1.-Y)
```

If gas has been added, then the temperature of the added gas is first calculated by assuming that the gas enters at cooling water temperature, TWI, and original pressure, P1(IG3) and then is compressed adiabatically to pressure PX. Next mass added, M2, is calculated from the perfect gas law. This pressure change affects all gas node temperatures for the adjusted working space since in this part of the calculation no heat transfer is allowed. Finally, the temperature of the cold space is adjusted because of the gas added.

```
592   C GAS INVENTORY CHANGE
593             IF(X)102,101,101
594   C TEMP  OF ADDED GAS
595   101       YY=TWI*(PX/P1(IG3))**GA
596   C MASS ADDED
597             M2=PX*X/(YY*XC)
598   C NEW TEMPERATURES DUE TO INVENTORY CHANGE
599   102       ZZ=(PX/P1(IG3))**GA
600             DO 807 K=1,8
601   807       TGA(1,K,IG3)=TGA(1,K,IG3)*ZZ
602   C ADJUSTMENT OF COLD SPACE TEMP  WITH GAS ADDITION
603             IF(X.GT.0)TGA(1,8,IG3)=(TGA(1,8,IG3)*W(1,8,IG3)+YY*M2)/
604        1    (W(1,8,IG3)+M2)
```

After the old pressure P1(IG3) is utilized for everything it needs to be, it is updated to the new pressure PX.

```
605   C NEW PRESSURE DUE TO INVENTORY CHANGE
606             P1(IG3)=PX
```

Next the cumulative volumes and the gas node inventories for the working space which is having its pressure changed (IG3) must be adjusted. The process is different depending on whether gas is added or removed. If gas added (X is greater or equal to zero), the cumulative volume of all the gas nodes except the last are reduced by the factor Y which in this case is less than 1. The total volume, CVG(8,IG3) does not change. The gas masses 1 to 7 do not change since all the added gas goes into node 8.

```
607:  C NEW CUM. VOL. AND GAS NODE INVENTORIES DUE TO GAS ADDED OR REMOVED
608:              IF(X)800,801,801
609:  C GAS ADDED OR NO CHANGE
610:  801         DO 802 K=1,7
611:  802         CVG(K,IG3)=CVG(K,IG3)*Y
612:              W(1,8,IG3)=W(1,8,IG3)+M2
613:              GOTO 803
```

If gas must be removed, any number of gas nodes can be removed and the remaining nodes can expand to take up the space. In this case Y, the volume ratio is greater than 1. Each cumulative volume is expanded by this ratio. However, when the cumulative volume CVG(K,IG3) first becomes greater than the total volume for that working space, CVM(8,IG3),then the mass of gas in this node is reduced depending upon the volume of this node still in the working space (lines 620 and 621). The total cumulative volume for that interpolated node becomes the total volume (line 625). Flag ZZ is used to make all subsequent gas nodes to have zero mass (line 624) and a cumulative gas volume equal to the total gas volume.

```
614:  C GAS REMOVED
615:  800         ZZ=1.
616:              DO 804 K=1,8
617:              CVG(K,IG3)=CVG(K,IG3)*Y
618:              IF(CVG(K,IG3)-CVM(8,IG3))804,804,806
619:  806         IF(ZZ)103,103,104
620:  104         W(1,K,IG3)=W(1,K,IG3)*(CVM(8,IG3)-CVG(K-1,IG3))/
621:           1  (CVG(K,IG3)-CVG(K-1,IG3))
622:              ZZ=0.
623:              GOTO 105
624:  103         W(1,K,IG3)=0.
625:  105         CVG(K,IG3)=CVM(8,IG3)
626:  804         CONTINUE
```

Finally, the new total mass for the working space must be re-added.

```
627:  C RE-ADD MASSES
628:  803         M(IG3)=0
629:              DO 119 K=1,8
630:  119         M(IG3)=M(IG3)+W(1,K,IG3)
```

For the case of gas being added the new value of M(IG3) has been calculated in line 597.

Step 3 - Volume Change--No Heat Transfer

In this method of analysis the process which occurs in the engine simultaneously is broken up into equivalent sequential steps. These are:

Step 3 - Volume Change with No Heat Transfer. Find the volumes of the gases that originally occupied each engine space before the volume change in Step 1. Find the temperature that each of the original nodes of gas now has due to an adiabatic expansion or compression.

Step 4 - Redefine the gas nodes due to gas flow. Find the mass and the mass average temperature of the gas now occupying each one of the gas spaces.

Step 5 - Allow heat transfer to take place in each one of the gas spaces if it is supposed to. To simplify calculation in this program, the hot and cold variable volume spaces are assumed to have no heat transfer and the other spaces are assumed to have perfect heat transfer. The heat transferred in each node goes to change the temperature of the metal nodes or is absorbed by the cooling water. No gas flow between nodes is allowed during this step so the heat capacity at constant volume is the proper one to use for the gas.

Step 6 - Due to heat transfer in Step 5 each node will have a different pressure. Step 6 calculates those pressures.

Step 7 - The ficticious barriers that have separated the nodes during Steps 5 and 6 are now removed. All gas nodes in each working space are allowed to come to a common pressure again. Step 7 calculates this common pressure.

Step 8 - The process of adiabatic pressure equilibration in Step 7 changes the temperature in each gas node. Step 8 calculates these final gas temperatures and prepares the calculation to srart through for another time step.

Now that the overall process has been explained, Step 3 will now be explained in detail.

The temperature-volume relationship for an adiabatic process is:

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

In the calculation CVG(8,I) is the original total volume for the Ith working space and CVM(8,I) is the new total volume as calculated in Step 1, line 584. After the new temperatures are calculated (line 639), all the cumulative gas volumes are adjusted proportional to the total gas volume change (line 642).

```
631    C STEP 3-DETERMINE PRESSURE, TEMPERATURE AND VOLUME CHANGES OF ORIGINAL
632    C     VOLUMES DUE TO TOTAL VOLUME CHANGE ASSUMING NO HEAT TRANSFER
633               DO290 I=1,4
634    C TOTAL VOLUME RATIO
635               XX(I)=CVG(8,I)/CVM(8,I)
636    C  NEW GAS TEMPERATURES
637               XT(I)=XX(I)**(KK-1)
638               DO 951 K=1,8
639    951        TGA(1,K,I)=TGA(1,K,I)*XT(I)
640    C  CUMULATIVE VOLUMES OF GAS NODES AFTER TOTAL VOLUME CHANGE
641               DO 983 K=1,8
642    983        CVG(K,I)=CVG(K,I)/XX(I)
643    290        CONTINUE
```

Step 4 - Computation of Mass Average Temperature and Mass of Gas Now in Each Engine Space Due to Gas Flow

Because of the volume changes and the adiabatic temperature changes like those shown in Figure 4.14 and because of gas inventory changes for control, there is mass flow.

It was found by experience that because of gas inflow for control that the programming must be able to handle mass flow across any number of nodes. That is, during one time step so much gas can be added to the cold space to push all the original gas into the hot space.

One of the important features of the program that was used as a model for this program was that the temperature was to vary linearly inside the gas nodes that were originally in the dead volumes of the engine. This idea was programmed and debugged but it was found that after several time steps, situations would develop which would result in a negative mass being assigned to a gas node which would result in a negative absolute pressure for that node. Since flow through several nodes during one time step will create certain inaccuracies, it was decided to simplify the programming and have all the gas in each gas node have an average temperature instead of a linear temperature gradient.

In order to be able to handle mass flow across any number of nodes, it was necessary to have a nomenclature where the volumes of the gas spaces are expressed as cumulative volume from the hot end. For instance, CVM(2,I) is the cumulative volume from the hot end to the interface between the heater manifold and the heater for the Ith working space. (See Figure 4.15.) The metal node temperatures TM(1,I) to TM(6,I) have already been discussed. TM(6,I) is fixed at the cooling water temperature TMI. All the other metal nodes float in temperature due to heat transfer by conduction and convection. During Step 4 it is convenient to define an average metal temperature for each part of the working space that transfers heat. For this purpose TMA(2,I) to TMA(7,I) are defined as midway between the metal node temperatures (see Figure 4.15).

At the start of the time step the gas nodes shown in Figure 4.15 all have the same volumes as the metal nodes. Up until now the mass in all these gas nodes has not changed except addition or removal of gas for control. (See Step 2.) However, because of motion of the pistons and gas inventory change, flow has taken place. During the time step up till now no heat transfer has taken place between the working gas and the metal so the temperature of the gas nodes will now be different from the metal nodes. In Figure 4.15 an adiabatic compression is assumed so that the temperature of all gas nodes is higher. However, the general shape of the temperature distribution is retained. For instance, in this particular program, the gas originally at TMA(2,I) attains the temperature TGA(1,2,I). (See Step 3.) Now with the cumulative volumes in arrays and the temperatures also in arrays one can program a general case that will determine the mass of gas in each engine space after mass flow and the mass average temperature of that gas.

To start out the programming one must start the main do loop for the four working spaces.

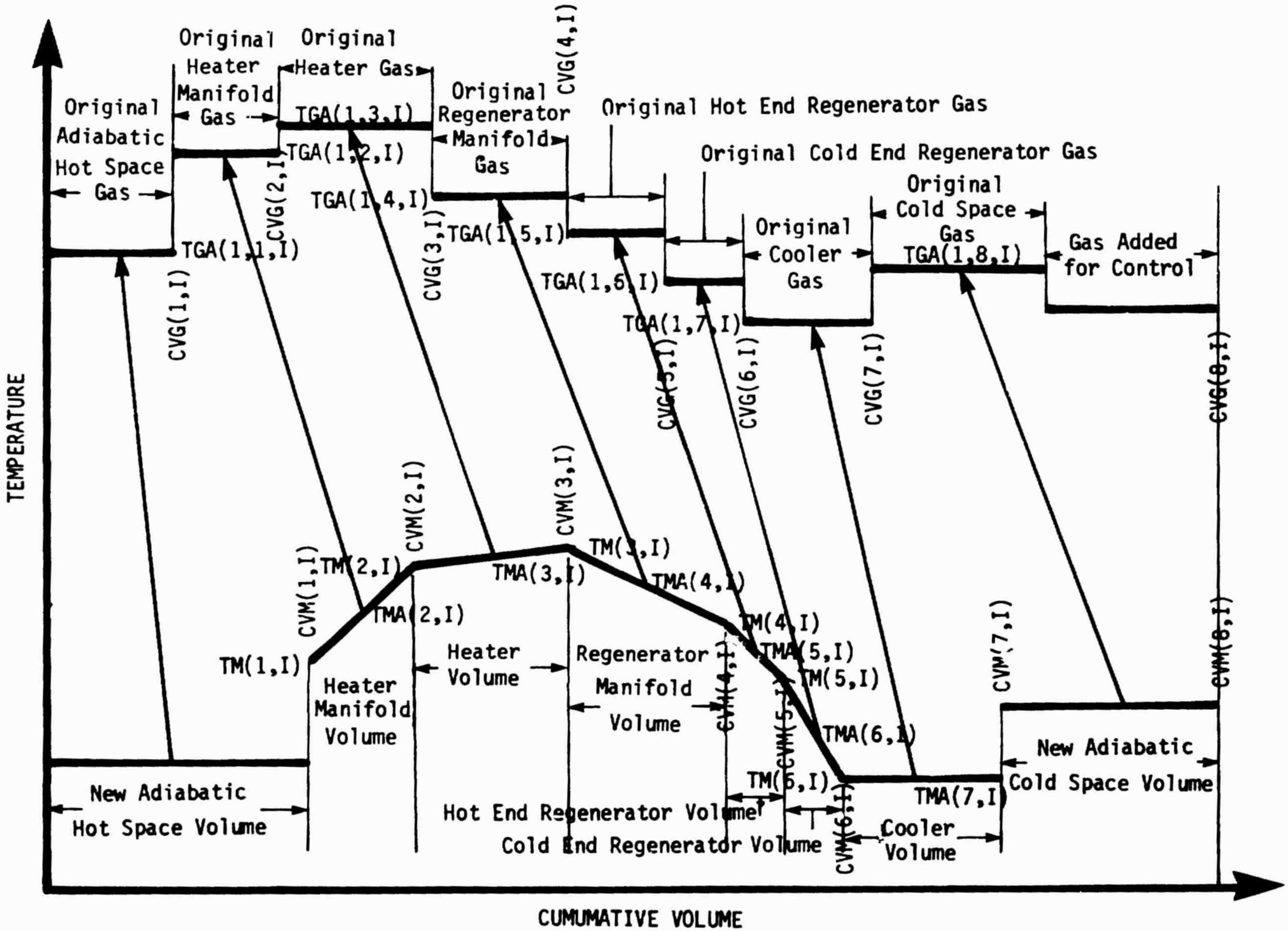


Figure 4.15. Nomenclature for Step 4.

```
C STEP 4--COMPUTATION OF TEMPERATURE AND MASS NOW IN EACH
C      ENGINE SPACE DUE TO GAS FLOW BUT NO HEAT TRANSFER
C      THIS VERSION ALLOWS UNLIMITED MASS FLOW DURING ONE TIME STEP
C CALCULATE FOR THE 4 WORKING SPACES
              DO 380 I=1,4
```

Next, two flags are initialized to 1. The K flag keeps track of the solid nodes and the L flag, the gas nodes. This arrangement is needed so that any number of gas nodes can be packed into a solid node or a gas node can be spread out over many solid nodes if required.

```
C LET K=SOLID INDEX AND L=GAS INDEX
              K=1
              L=1
```

Then the gas inventory array at the end of the time step W(2,X,I) and the average gas temperature array at the end of the time step are zeroed.

```
C ZERO OUT MASS ARRAY AFTER MASS FLOW
              DO 349 II=1,8
              TGA(2,II,I)=0.
       349    W(2,II,I)=0
```

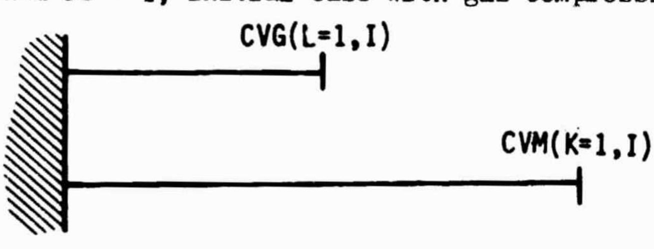
In apportioning the masses it was found that the first time through a particular part of the program was different than the next time. Therefore, a second time flag was found necessary. This is initialized.

```
C SET SECOND TIME FLAG
              II=1
```

For each working space we start with the first gas node and the first metal node. We keep adding nodes to the one with the least volume until both gas and metal have 8 nodes. When this is so, the program for that working space is complete. The decision point compares the cumulative volume in the gas for L nodes to the cumulative volume in the engine metal for K nodes. The cumulative gas volume can be less than exactly equal to or greater than the cumulative metal volume.

```
C RETURN POINT OF DECISION TREE
       348    IF(CVG(L,I)-CVM(K,I))345,346,347
```

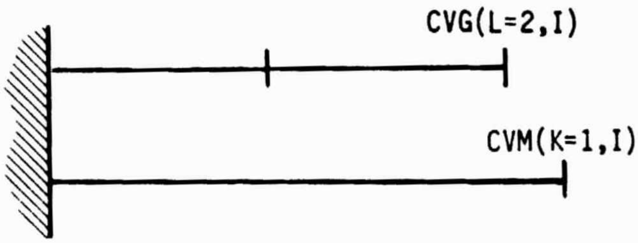
Now the three possible cases will be discussed in the order they appear in the program. We will first discuss the case when the cumulative gas volume is less than the cumulative metal volume. For instance, take the case where K = 1, L = 1 and II = 1, initial case with gas compression.



In this case Y = W(2,K,I) = 0. The new average temperature TGA(2,K,I) is simply TG(1,L,I). The L or gas index is incremented. If L is greater or equal to 9, the solution is completed. If not, the solution returns to the top of the decision tree (line 659).

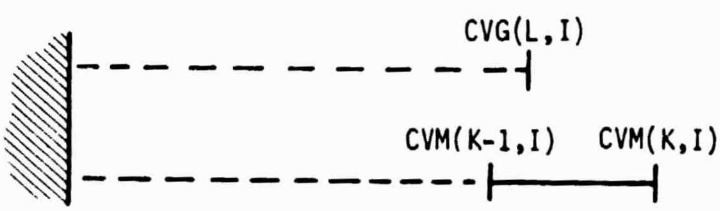
```
660:   C**** CUM. GAS VOL. LESS THAN CUM. METAL VOLUME.
661:   345       IF(II)354,354,355
662:   354       II=1
663:             W(2,K,I)=PM
664:             TGA(2,K,I)=TGA(1,L,I)
665:             GOTO358
666:   355       Y=W(2,K,I)
667:             W(2,K,I)=W(2,K,I)+W(1,L,I)
668:             TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*W(1,L,I))/W(2,K,I)
669:   358       CONTINUE
670:   C INDEX GAS NODE FLAG AND RETURN
671:             L=L+1
672:   C CHECK FOR END OF MASS FLOW CALCULATION
673:             IF(L.GE.9) GOTO 310
674:   C RETURN
675:             GOTO 348
```

If the next time through the cumulative volume of the gas is still less than the metal space it is filling, in this case the hot space, the calculation still goes through the same parts of the program.



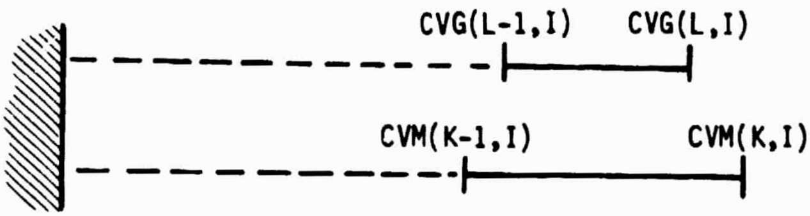
Now this time through W(2,K,I) is the mass of gas in the hot space with the first two gas nodes being considered. TGA(2,K,I) is the average temperature in the hot space so far.

The other half of the programming given above (lines 659-663) cannot be entered from the beginning of the calculation. During the calculation, addition of a metal node makes the metal node cumulative volume greater than the gas node culculative volumes.



When this happens, the flag II is set to zero (see line 723) and the calculation enters this other part of the program. A new mass W(2,K,I) starts to be accumulated by the addition first of residual mass or the gas mass hanging over when the gas in node K-1 was completely calculated. The average gas temperature calculation is also initiated with the temperature of gas node L. L is indexed by one and the calculation may come back through again.

If the next gas node still makes CVM(K,I) > CVG(L,I) as in the sketch below, then the calculation goes back through lines 666-669 because now II = 1. That is, it is the second time for the new metal volume node. This programming adds to the calculation of the mass and the average temperature in a particular engine volume but never finishes it.



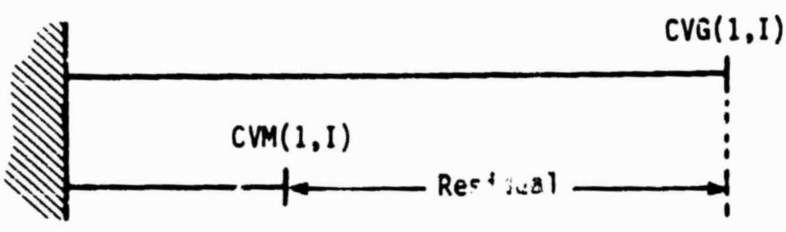
The cumulative volumes may sometimes be exactly equal during the calculation. Quite often when both K and L are 8, the cumulative volumes will match exactly. Generally, this programming is the same as previous programming. The first time flag is set to 1 and both K and L flags are indexed. The calculation is ended if K or L are greater or equal to 9. In most cases both would be 9.

```
C***** CUM GAS VOL EXACTLY EQUAL TO CUM METAL VOLUME
C CHECK FIRST TIME FLAG
[illegible]       IF(II)810,810,850
C ADDITION OF METAL NODE LEADS TO EQUAL VOLUMES
810       W(2,K,I)=RM
          TGA(2,K,I)=TGA(1,L,I)
          GOTO 851
C ADDITION OF GAS NODE LEADS TO EQUAL VOLUMES
C FIND MASS TO COMPLETE METAL NODE SPACE
[illegible]       [illegible]
          [illegible]
C FIND AVERAGE TEMP. OF GAS NOW IN METAL NODE SPACE
          [illegible]
C SET FIRST FLAG
851       II=1
C INDEX [illegible] AND GAS NODE FLAGS
          [illegible]+1
          [illegible]+1
C CHECK FOR END OF MASS FLOW CALCULATION
          IF(K.GE.9.OR.L.GE.9) GOTO [illegible]
C RETURN
          [illegible]
```

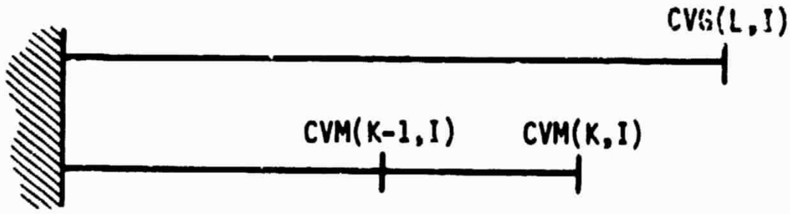
The final possibility is that the cumulative gas volume can be greater than the cumulative metal volume. The way the programming was done there is a special case when K L = 1 and a general case.

For the special case as shown below, the mass W(2,K,I) is a fraction of W(1,L,I) based upon the volumes. The average gas temperature is transferred over directly. The residual mass is that hanging over. The second time flag II is set to zero and K is indexed by one.

```
C**** CUM. GAS VOL. GREATER THAN CUM. METAL VOLUME
347      IF(K.EQ.1.AND.L.EQ.1) GOTO 350
         GOTO 351
C FIRST NODE FOR GAS AND METAL
350      W(2,K,I)=W(1,L,I)*CVM(K,I)/CVG(L,I)
         TGA(2,K,I)=TGA(1,L,I)
         RM=W(1,L,I)-W(2,K,I)
         GOTO 357
C GENERAL CASE
C CHECK FIRST TIME FLAG
351      IF(II)343,343,344
C FIRST TIME FOR NEW GAS NODE
344      RR=(CVM(K,I)-CVG(L-1,I))/(CVG(L,I)-CVG(L-1,I))
         RM=(1.-RR)*W(1,L,I)
         X=RR*W(1,L,I)
         Y=W(2,K,I)
         W(2,K,I)=W(2,K,I)+X
         TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*X)/W(2,K,I)
         GOTO 357
C AFTER THE FIRST TIME
343      RR=(CVM(K,I)-CVM(K-1,I))/(CVG(L,I)-CVM(K-1,I))
         W(2,K,I)=RM*RR
         RM=RM-W(2,K,I)
         TGA(2,K,I)=TGA(1,L,I)
C RESET FIRST FLAG ON GAS VOLUME SHORT SIDE
357      II=0
C INDEX SOLID NODE FLAG
         K=K+1
C CHECK FOR END OF FLOW CALCULATION
         IF(K.GE.9) GOTO 310
C RETURN
         GOTO 348
```

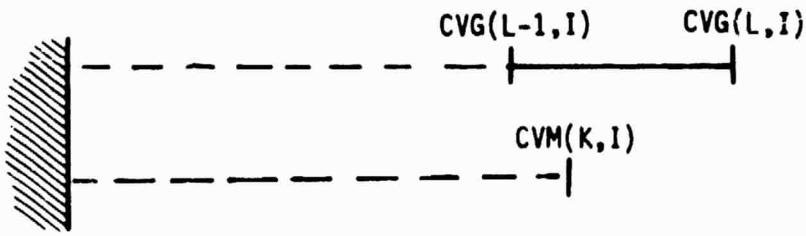


Now for the next node K = 2 and L = 1 and II = 0.



Therefore, it would go through lines 717-721. RR is the fraction of the residual volume that is assignable to W(2,K,I). Therefore, a new residual mass, RM, is calculated for that still hanging over. Gas temperature is transferred across.

During the course of the calculation, indexing of L leads to the case where CVG(L,K) > CVM(K,I). Thus:



In this case (lines 709-716) RR is the fraction of W(1,L,I) that it takes to finish W(2,K,I). The rest is made the residual mass. The final average gas temperature is calculated for that node using the mass and the average temperature up to that point and the new mass and average temperature.

With all this complicated programming for transferring masses during Step 4, there were many chances for error. Therefore, an error trapping routine is introduced at this point which will stop the program and print out some intermediate results if mass is changed during this step. All the masses are summed and compared with the previous mass sum. If the total mass is off by more than 0.1 gram, then it will write out the flow error and the working space it has occurred in. Other intermediate values are printed out to show the operator what the problem is. See the operator manual (Section 6) for additional details. This error tracking program was very useful in the debugging of this program.

```
C FIND AND SHOW TOTAL MASS AFTER MASS FLOW
310      X=0
         DO 326 K=1,8
326      X=X+W(2,K,I)
         ERRFL=M(I)-X
         IF(ABS(ERRFL)- 1)380,380,329
329      WRITE(J,330)ERRFL,I
330      FORMAT(' FLOW ERROR IS' E10.4,' IN WORKING SPACE #' I2)
         DO 153 K=1,8
153      WRITE(J,154)K,W(1,K,I),W(2,K,I),CVM(K,I),CVG(K,I),
       1 TGA(1,K,I),TGA(2,K,I)
154      FORMAT(I3,6F10.4)
         STOP
380      CONTINUE
```

Step 5 - Change in Temperature of Gas and Metal Nodes Due to Heat Transfer with No Volume Change

Note again that metal nodes 1 to 5 float. That is, as they receive heat their temperature rises; as they loose heat their temperature falls. Also, note again that it is assumed that the gas in the heater manifold, heater, regenerator manifold, regenerator and cooler attains the temperature of the metal during this step. To simplify calculation the amount of heat transferred to each metal node is calculated first. Then the metal node temperatures are adjusted according to their heat capacity.

The heat transferred by changing the gas temperature to the average temperature of the heater manifold is assumed to be transferred half to metal node 1 and half to metal node 2. The amount of heat transfer is based upon the gas mass now between the metal node points. The heat capacity of this gas is taken at constant volume. For instance, the temperature drop for node 2 is from the temperature of the gas calculated to be in the heater manifold at the end of Step 4 and to the average temperature of metal nodes 1 and 2.

The heat received (or given up) by the other metal nodes is computed similarly. Note that this is being done for the four working spaces.

```
C STEP 5 - CHANGE IN TEMPERATURE OF GAS AND METAL NODES DUE TO
C         HEAT TRANSFER WITH NO VOLUME CHANGE
C  IN GAS COOLER
         DO [illegible]
C HEAT RECEIVED BY METAL NODE 1
         QM(1)=[illegible]TGA(2[illegible]TM[illegible]
C HEAT RECEIVED BY METAL NODE 2
         [illegible]TGA[illegible]TM[illegible]
         QM(2)=QM(1)[illegible]
C HEAT RECEIVED BY METAL NODE 3
         [illegible]TGA[illegible]TM[illegible]
         QM(3)[illegible]
C HEAT RECEIVED BY METAL NODE [illegible]
         [illegible]TGA[illegible]TM[illegible]
         QM(4)[illegible]
```

```
C HEAT RECEIVED BY METAL NODE 5
          Y=CV*W(2,6,I)*(TGA(2,6,I)-TMA(6,I))/2.
          OM(5)=X+Y
C HEAT RECEIVED BY METAL NODE 6
          X=CV*W(2,7,I)*(TGA(2,7,I)-TMA(7,I))/2.
          OM(6)=Y+X
C HEAT RECEIVED BY METAL NODE 7
          OM(7)=X
```

Next, it is now assumed that the gas in each space of each compartment except the gas in the adiabatic spaces attains the average temperature of the metal in that space.

```
C CHANGE IN AVERAGE GAS TEMPERATURES DUE TO HEAT TRANSFER
          DO 363 K=2,7
  363     TGA(2,K,I)=TMA(K,I)
```

Finally, the metal node temperatures are changed due to heat transfer between the working gas and the metal.

```
C CHANGE IN METAL NODE TEMPERATURES DUE TO HEAT TRANSFER
          DO 382 K=1,5
          TM(K,I)=TM(K,I)+OM(K)/CM(K)
  382     CONTINUE
  400     CONTINUE
```

Step 6 - New Pressures for Each Space Due to Heat Transfer with No Volume Change

The gas temperature changes in Step 5 were done with each gas node isolated. Therefore, each gas node will have a different pressure. In Step 6 these pressures are calculated using the perfect gas law.

```
C STEP 6--NEW PRESSURES FOR EACH SPACE DUE TO HEAT TRANSFER WITH NO
C         VOLUME CHANGE
          DO 740 I=1,4
C    HOT SPACE
          PI(I,1)=W(2,1,I)*RC*TGA(2,1,I)/VHA(2,I)
C    HEATER MANIFOLD
          PI(I,2)=W(2,2,I)*RC*TGA(2,2,I)/VHM
C    HEATER
          PI(I,3)=W(2,3,I)*RC*TGA(2,3,I)/VHD
C    REGENERATOR MANIFOLD
          PI(I,4)=W(2,4,I)*RC*TGA(2,4,I)/VRM
C    REGENERATOR HOT HALF
          PI(I,5)=W(2,5,I)*RC*TGA(2,5,I)/(VRD/2.)
C    REGENERATOR COLD HALF
          PI(I,6)=W(2,6,I)*RC*TGA(2,6,I)/(VRD/2.)
C    COOLER
          PI(I,7)=W(2,7,I)*RC*TGA(2,7,I)/VCD
C    COLD SPACE
          PI(I,8)=W(2,8,I)*RC*TGA(2,8,I)/VCA(2,I)
```

Step 7 - Adiabatic Pressure Equilibration at Constant Total Volume

Now in Step 7 the barriers between the nodes are removed. Assuming adiabatic processes, it is possible to solve algebraicly for a common pressure for all the nodes. Start with the adiabatic relationship

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^k \quad , \; k = CP/CV$$

Using the nomenclature of the program the gas originally in the hot space now has a volume of

V1(I) = VHA(2,K) * (P3(I,1)/P4(I)) ** KR

The gas originally in the heater manifold now has a volume of

V2(I) = VHM * (P3(I,2)/P4(I)) ** KR

The heater:

V3(I) = VHD * (P3(I,3)/P4(I)) ** KR

The regenerator manifold:

V4(I) = VRM * (P3(I,4)/P4(I)) ** KR

The hot half of the regenerator:

V5(I) = VRD/2 * (P3(I,5)/P4(I)) ** KR

The cold half of the regenerator:

V6(I) = VRD/2 * (P3(I,6)/P4(I)) ** KR

The cooler:

V7(I) = VCD * (P3(I,7)/P4(I)) ** KR

The cold space:

V8(I) = VCA(2,I) * (P3(I,8)/P4(I)) ** KR

Now the total volume has not changed. Therefore:

VT(2,I) = V1(I) + V2(I) + V3(I) + V4(I) + V5(I) + V6(I)

+ V7(I) + V8(I)

The unknown P4(I) is solved for in the above equations. See the programming below.

```
794    C STEP 7--ADIABATIC PRESSURE EQUILIBRATION AT CONSTANT TOTAL VOLUME
795    C    FINAL COMMON PRESSURE FOR INCREMENT
796               X=VHA(2,I)*P3(I,1)**KR
797               X=X+VHM*P3(I,2)**KR
798               X=X+VHD*P3(I,3)**KR
799               X=X+VRM*P3(I,4)**KR
800               X=X+VRD(2)*P3(I,5)**KR
801               X=X+VRD(2)*P3(I,6)**KR
802               X=X+VCD*P3(I,7)**KR
803               X=X+VCA(2,I)*P3(I,8)**KR
804               P4(I)=(X/VT(2,I))**KK
```

Step 7A - New Temperatures

This pressure equilibration step results in different temperatures for each gas node. Using the adiabatic relationship these temperatures are calculated.

```
805    C STEP 7A-- GAS NODE TEMPERATURES AFTER ADIABATIC PRESSURE
806    C                EQUILIBRATION
807               DO 173 K=1,8
808     173       TGA(2,K,I)=TGA(2,K,I)*(P4(I)/P3(I,K))**GA
```

Step 7B - New Volumes

With a new pressure and new temperatures, new gas node volumes and cumulative volumes are now calculated.

```
809    C STEP 7B-- CUMULATIVE VOLUMES OF GAS NODES DUE TO PRESSURE
810    C                EQUILIBRATION
811               CVG(1,I)=W(2,1,I)*XC*TGA(2,1,I)/P4(I)
812               DO 174 K=2,8
813     174       CVG(K,I)=CVG(K-1,I)+W(2,K,I)*XC*TGA(2,K,I)/P4(I)
```

Finally, since CVG(8,I) by the above series of calculations may have an accumulated error, the correct value is substituted.

```
814    C CORRECT SMALL ERROR IN VOLUME
815               CVG(8,I)=VT(2,I)
```

Step 8 - Initialize Quantities for Next Increment

Because of the way the calculation was formulated, the temperatures, volumes, pressures and masses in the four working spaces and in the eight nodes in each working space could not be modified as the calculation progressed. A difference had to be made between the old and new values. In this step these values are reinitialized. Note that Steps 6, 7 and 8 are in one do loop (lines 777 to 829). Therefore, these steps are done for working space 1, I = 1, and then for working space 2, I = 2, and so on.

```
      C STEP 8-- INITIALIZE QUANTITIES FOR NEXT INCREMENT
      C    TEMPERATURE
               DO 364 K=1,8
      364      TGA(1,K,I)=TGA(2,K,I)
      C    VOLUMES
               VT(1,I)=VT(2,I)
               VCA(1,I)=VCA(2,I)
               VHA(1,I)=VHA(2,I)
      C    PRESSURES
               P1(I)=P4(I)
      C    MASSES
               DO 750 K=1,8
      750      W(1,K,I)=W(2,K,I)
      740      CONTINUE
```

Step 9 - Determine Engine Torque at Output Shaft

This step is the culmination of a large amount of calculation. It proceeds in three steps: 1) find the forces on the pistons, 2) find the torques and average pressure, 3) find the shaft torque from the indicated torque based upon a correlation.

The force on a particular piston is the net of three forces: 1) the pressure times the area of the hot end of the piston (ACY), 2) the pressure of the next working space times the area of the bottom of the piston (BCY) taking out for the drive rod, and 3) the pressure drop across the seal times the seal area (CCY). In this program the crank case pressure is fixed at 0.1 MPa = 1 atm. Since the pressures are in megapascals, 10^6 N/m^2, and the areas are in cm^2, a factor of 100 is needed to convert the units. Figure 4.16 shows that the forces on the pistons are all upward for a positive force.

```
      C STEP 9--DETERMINE ENGINE TORQUE AT OUTPUT SHAFT
      C   INDICATED ENGINE TORQUE, FORCE ON PISTONS, NEWTONS
               FP(1)=100.+(-P1(1)+ACY+P1(4)+BCY-(P1(4)-0.1)+CCY)
               FP(2)=100.+(P1(1)+BCY-P1(2)+ACY-(P1(1)-0.1)+CCY)
               FP(3)=100.+(P1(2)+BCY-P1(3)+ACY-(P1(2)-0.1)+CCY)
               FP(4)=100.+(P1(3)+BCY-P1(4)+ACY-(P1(3)-0.1)+CCY)
```

Next, these forces are converted to a torque from each crank. The angle convention is that used in Figure 4.14. Note that since the radius of the crank, RC, is in centimeters, division by 100 is needed to obtain the torque in Newton-meters.

```
      C   TORQUE ON EACH CRANK, N-M, CCW IS POSITIVE
               TQ(1)=RC/100.+SIN(EARAD)+FP(1)
               TQ(2)=RC/100.+SIN(EARAD+PI2)+FP(2)
               TQ(3)=RC/100.+SIN(EARAD+PI)+FP(3)
               TQ(4)=RC/100.+SIN(EARAD+PI32)+FP(4)
```

Next, the indicated torque is the sum of the four crank torques. The average pressure is calculated to be used in the shaft torque calculation.

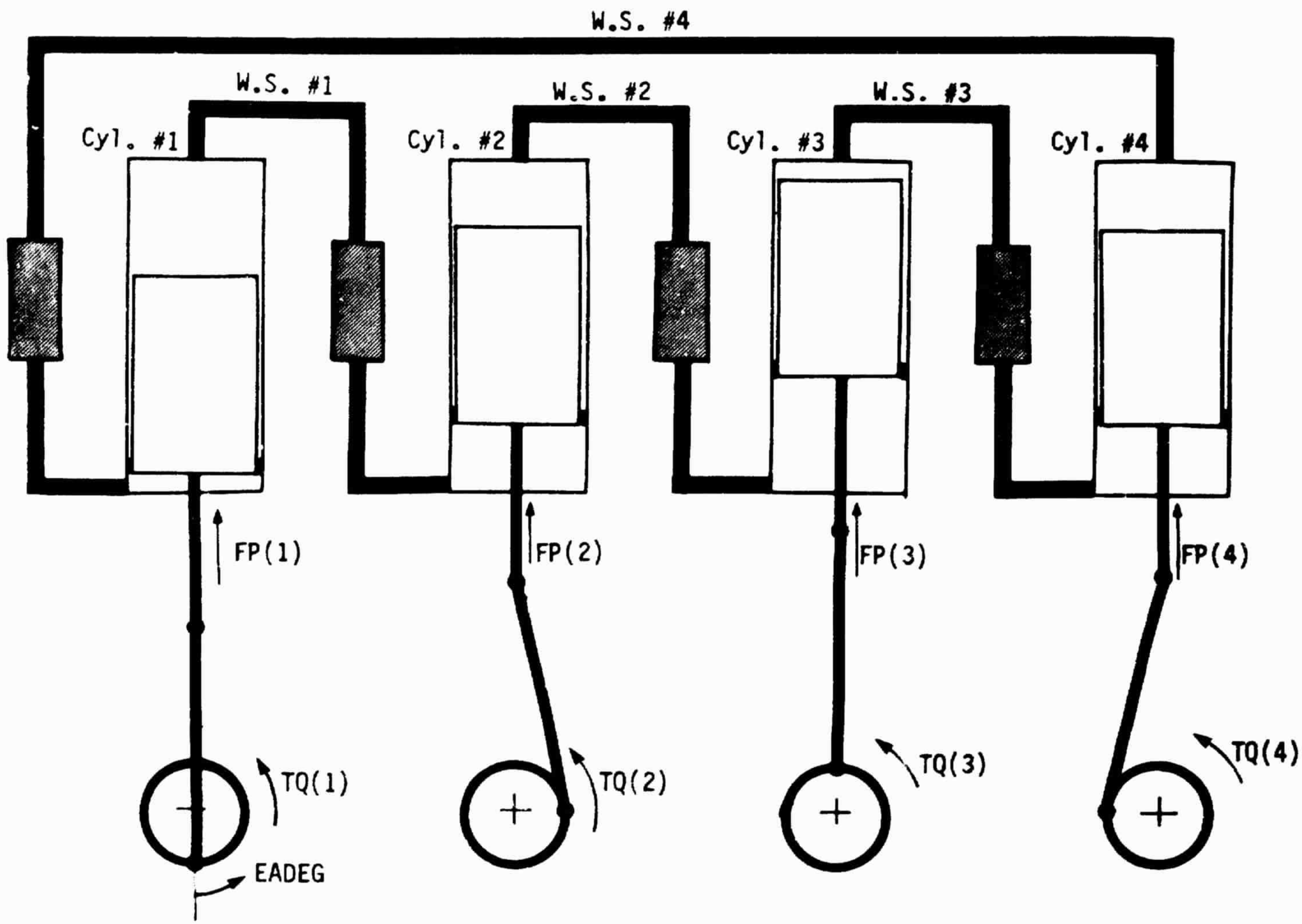


Figure 4.16. Force on Pistons and Engine Torque Calculations.

```
C   INDICATED TORQUE FOR ENGINE
            TQI=TQ(1)+TQ(2)+TQ(3)+TQ(4)
            PAV=(P1(1)+P1(2)+P1(3)+P1(4))/4.
```

In order to avoid calculating flow losses all the way along, a correlation was made for the 4L23 engine to determine how the power drop due to flow losses correlates with engine pressure and speed. This correlation was based upon 16 cases run with the isothermal second-order analysis (6). This analysis was found to agree with the validated General Motors calculation to within 10% over the full range of engine operation (6). Appendix B fully explains this correlation and show that it is nearly exact.

```
C   SHAFT TORQUE FOR ENGINE
            SP=OMEG/(2.*PI)
            TQS=TQI*ME/100.*(.99862-.0000145*OMEG**2)*(1.-OMEG*.000491*
         1  PAV**(-1.841))
C*****END OF ENGINE TORQUE AND INTERNAL H.T. SUBPROGRAM
```

4.2.10 Control Program (Part 3)

This very simply asks if time is up. If not, it starts over.

```
C*****CONTROL PROGRAM PART 3
790         IF(TIM-TOTT)401,795,795
```

4.2.11 Final Summary Report

The final summary report is now very simple. It simply prints the total fuel consumed, the total time (given) and the ending vehicle speed. More information can be added as the need is felt.

```
C*****FINAL SUMMARY REPORT
795         WRITE(1,798)FUEL,TOTT,SPV1
798         FORMAT(' FUEL,TOTT,SPV1',3F10.3)
5000        STOP
            END
```

5.0 LISTING OF PROGRAMS

Three separate computer codes are included in this report. One code, WARM, was used to evaluate how best to handle the burner and air preheater. This code is given in Appendix A along with an explanation of it and the results found from it.

Listings are given in this section for CNTLA.FOR and CNTLB.FOR. CNTLA contains the nomenclature for both programs. CNTLA.FOR is given on pages 73 to 86. CNTLB.FOR is given on pages 88 to 104. CNTLB.FOR was given piecemeal in Section 4 as the equations were explained.

FORTRAN SOURCE CODE LISTING

OF CNTLA

```
C PROGRAM CNTLA.FOR
C WRITTEN BY MARTINI ENGINEERING UNDER CONTRACT NUMBER
C DEN3-2A6 FOR NASA-LEWIS UNDER THE DOE ADVANCED AUTOMOTIVE
C PROPULSION PROGRAM.  THIS PROGRAM SHOWS NOMENLCATURE FOR
C CNTLA AND CNTLB.   CNTLA IS FOR CHANGING INPUT PARAMENTES
C FROM THE CONSOLE AND IS FOR CREATING A DATA FILE TO BE
C READ BY CNTLB.
C         ***** NOMENCLATURE *****
C    A = TEMPORARY VARIABLE
C    AAPH = HEAT TRANSFER AREA OF FULL AIR PREHEATER, SQ CM
C    ACE = RADIAL ENGINE ACCELERATION, RAD/SEC**2
C    ACR = ANGLE INCREMENT CRITERIA, DEGREES
C    ACRR = ANGLE INCREMENT CRITERIA, RADIANS
C    ACV = ACCELERATION OF VEHICLE AT START OF TIME STEP, M/SEC**2
C    ACY = PI4*DCY**2
C    AF = AIR FRICTION, NEWTONS
C    AFAPH = AIR FLOW AREA FOR AIR PREHEATER, SQ CM
C    AFR = FRONTAL AREA OF VEHICLE TIMES SHAPE COEFFICIENT, M**2
C    AH = HEAT TRANSFER AREA FROM FLAME, FULL ENGINE, SQ CM
C    AMF = GAS HEATER MINIMUM FLOW AREA, CM**2
C    B = TEMPORARY VARIABLE
C    BCY = PI4*(DCY**2-DDR**2)
C    C = TEMPORARY VARIABLE
C    CCY = ACY-BCY
C    CFF = CURRENT FUEL FLOW, G/S
C    CFH = FUEL FLOW ABOVE WHICH NEW HEAT TRANSFER FACTORS
C       MUST BE CALCULATED, G/S
C    CFL = FUEL FLOW BELOW WHICH NEW HEAT TRANSFER FACTORS
C       MUST BE CALCULATED, G/S
C    CM(5) = METAL NODE HEAT CAPACITIES, J/K
C    CMH = HEAT CAPACITY OF GAS HEATERS FOR ONE CYLINDER, J/K
C    CMAPH = HEAT CAPACITY OF APH METAL NODE, J/K
C    CMX = HEAT CAPACITY OF REGENERATOR MATRIX, J/K
C    CP = HEAT CAPACITY AT CONSTANT PRESSURE, J/G K
C    CPA = HEAT CAPACITY OF AIR, J/G K
C    CPFG = HEAT CAPACITY OF FLUE GAS, J/G K
C    CS = COEFFICIENT FOR SHAPE OF VEHICLE
C    CV = HEAT CAPACITY AT CONSTANT VOLUME, J/G K
C    CYY = 4.*CZ*DT/CMAPH
C    DANG = CHANGE IN ENGINE ANGLE, RAD
C    DCY = DIAMETER OF CYLINDER, CM
C    DDR = DIAMETER OF DRIVE ROD, CM
C    DDT = TIME STEP IN ENGINE CALCULATION TO MAKE DANG BETWEEN
C          10 AND 20 DEGREES, SEC
C    DEQ = EQUIVALENT DIAMETER (USED IN AIR PREHEATER), CM
C    DIC = DIAMETER INSIDE OF COOLER TUBES, CM
C    DIH = DIAMETER INSIDE OF HEATER TUBES, CM
C    DIHM = INSIDE DIAMETER OF TUBES IN HEATER MAN.,CM
C    DIRM = INSIDE DIAMETER OF TUBES IN REGEN  MAN.,CM
C    DIST = DISTANCE TRAVELED FROM START, M
C    DOH = OUTSIDE DIAMETER OF HEATER TUBES, CM
C    DR = DIAMETER OF EACH REGENERATOR, CM
C    DST = DISTANCE TRAVELED DURING TIME STEP, M
C    DT = TIME STEP, INITIAL AND STANDARD, SEC
C    EADEG = ENGINE ANGLE, DEGREES
C    EARAD = ENGINE ANGLE, RADIANS
```

```
C     EIN = ENGINE INERTIA, KG*M**2
C     ERRFL = ERROR IN FLOW MASS BALANCE, GM
C     EX(Y) = AIR PREHEATER METAL NODE TEMPS. AT START OF TIME STEP,K
C     EY(Y) = AIR PREHEATER METAL NODE TEMPS. AT END OF TIME STEP, K
C     FCA = FRACTION OF VCDX THAT IS ADIABATIC
C     FF = FILLER FACTOR, FRACTION OF REGENERATOR VOLUME FILLED
C          WITH SOLID, MUST BE ZERO IF IT IS NOT KNOWN
C     FFF = FULL FUEL FLOW, G/S
C     FLAME = BURNER FLAME TEMPERATURE, K
C     FP(4) = FORCE ON PISTONS(AWAY FROM CRANKSHAFT IS POSITIVE)
C             NEWTONS
C     FUEL = TOTAL FUEL CONSUMED BY ENGINE, G
C     FWI = FLOW, WATER INLET FOR ENTIRE ENGINE, G/SEC
C     G = GAP BETWEEN HOT CAP AND CYLINDER WALL, CM
C     GA = (KK-1)/KK
C     GAPH = MASS VELOCITY (USED IN AIR PREHEATER), G/S CM**2
C     GCT = GEAR CHANGE TIME, SEC
C     GDF = GRAPHIC DISPLAY FLAG, SEC
C     GDI = GRAPHIC DISPLAY INCREMENT, SEC
C     GMAX = MAXIMUM MASS VELOCITY IN HEATER, G/S CM**2
C     HAS = HEAT TRANSFER COEFFICIENT, W/K CM**2
C     HCL = HOT CAP LENGTH, CM
C     I = TEMPORARY INTERGER VARIABLE
C     II = TEMPORARY INTEGER VARIABLE
C     IG1 = FLAG 0=HEAT UP, 1=IDLE, 2=IN GEAR
C     IG2 = FLAG 0=INITIAL VALUE, 1=AFTER CALC INITIAL GAS MASSES
C     IG3 = FLAG SHOWING WORKING SPACE IN WHICH GAS MASS WAS CHANGED
C     J = PRINTOUT FLAG--5 TO SCREEN, 2 TO PRINTER, INTEGER
C     I1,I2 = GRAPHIC OUTPUT, X VALUES
C     IPV(2,4) = GRAPHIC OUTPUT ARRAY FOR PV DIAGRAM
C     J1,J2 = GRAPHIC OUTPUT, Y VALUES
C     JPV(2,4) = GRAPHIC OUTPUT ARRAY FOR PV DIAGRAM
C     J7 = DETERMINES INPUT NUMBER SELECTION
C     K = TEMPORARY INTEGER VARIABLE, SOLID INDEX COUNTER
C     KAPH = THERMAL COND. FACTOR IN APH, W/K
C     KAR = COEFFICIENT OF AIR RESISTANCE
C     KK = CP/CV
C     KM = THERMAL CONDUCTIVITY OF STRUCT. MAT., W/CM K
C     KME(6) = THERMAL CONDUCTIVITY FACTOR FOR ENGINE METAL NODES W/K
C     KMX = THERMAL CONDUCTIVITY OF MATRIX MAT., W/CM K
C     KR = 1 / KK
C     L = GAS INDEX COUNTER
C     LAPH = HEAT TRANSFER LENGTH IN AIR PREHEATER, CM
C     LC = LENGTH OF COOLER TUBES, CM
C     LCR = LENGTH OF CONNECTING ROD, CM
C     LH = LENGTH OF HEATER TUBES, CM
C     LHH = HEATED LENGTH OF HEATER TUBES, CM
C     LHM = LENGTH OF TUBES IN HEATER MANIFOLD, CM
C     LHV = LOWER HEATING VALUE OF FUEL, KJ/G
C     LR = LENGTH OF REGENERATOR, CM
C     LRM = LENGTH OF TUBES IN REGENERATOR MAN.,CM
C     M(4) = INVENTORY OF GAS IN EACH ENGINE COMPARTMENT, G
C     M2 = GAS MASS CHANGE, G
C     ME = ENGINE MECHANICAL EFFICIENCY, PERCENT
C     MGI = INITIAL GAS INVENTORY, G
C     MIR = BASIC TIME CONSTANT IN ADDING OR REMOVING GAS
C     MIR1 = ADJUSTMENT OF MIR TO PREVENT CONTROL OVERSHOOT
C     MIV = MASS, INERTIA OF VEHICLE, KG
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C     MM1 = MASS OF GAS MOVED ACROSS NODE 1 IN COLD DIRECTION
C     MM2 TO MM7 = SAME FOR NODES 2 TO 7
C     MSH = MESH SIZE, WIRES/CM
C     MW = MOLECULAR WEIGHT OF WORKING GAS, G/G MOLE
C     MWFG = MOLECULAR WEIGHT OF FLUE GAS, G/G MOLE
C     N = NUMBER OF NODES IN AIR PREHEATER, INTEGER
C     NAPH = # OF AIR PREHEATER FLOW PASSAGES IN EACH DIRECTION
C     NER = FLAG TO COUNT NUMBER OF CYCLES BEFORE ERASING PV DIAG
C     NGC = GEAR CHANGE FLAG, INTEGER
C     NO = NUMBER OF NODES IN AIR PREHEATER, REAL
C     NO2 = N/2
C     NR = NUMBER OF REGENERATORS/CYLINDER
C     NS = NUMBER OF SCREENS PER REGENERATOR
C     NTC = NUMBER OF COOLER TUBES/CYLINDER
C     NTH = NUMBER OF HEATER TUBES PER CYLINDER
C     NTRM = NUMBER OF TUBES IN REGENERATOR MANIFOLD
C     OM1 = DESIRED IDLE SPEED OF ENGINE, R/S
C     OMEG = ACTUAL ENGINE SPEED, R/S
C     PAV = AVERAGE PRESSURE IN 4 CYLINDERS, MPA
C     PBIS = PROPORTIONAL BAND, IDLE SPEED, RAD/SEC
C     PBVS = PROPORTIONAL BAND, VEHICLE SPEED, M/SEC
C     PDIF = PRH-PRL
C     PI = PI = 3.141592654
C     PI2 = PI/2 = 1.570796327
C     PI32 = 3*PI/2
C     PI4 = PI / 4 = .7853981635
C     POF = PRINT OUT FLAG, SEC
C     PRH = HIGH PRESSURE RESERVOIR PRESSURE, MPA
C     PRL = LOW PRESSURE RESERVOIR PRESSURE, MPA
C     PS = GAS PRESSURE OF WORKING SPACE HAVING ITS PRES. ADJ.,MPA
C     P1(4) = GAS PRESSURE AT BEGINNING OF TIME STEP, MPA
C     P2(4) = GAS PRESSURE AFTER VOLUME CHANGE, MPA
C     P3(4,8) = GAS PRESSURE AFTER TEMPERATURE EQUILIBRATION AT
C                 CONSTANT VOLUME, MPA
C     P4(4) = COMMON GAS PRESSURE AT END OF TIME STEP, MPA
C     Q1 = OUTPUT FLAG, 1.0=GRAPHICS ON SCREEN, REAL
C     Q2 = PRINTOUT FLAG, 5.00 TO SCREEN, 2.00 TO PRINTER
C     Q3 = OUTPUT FLAG, 1.0=PERIODIC PRINTOUT, 0.0=NONE
C     QE = HEATING OF HEATER TUBES OF ONE CYLINDER BY BURNER
C           DURING A TIME STEP, J
C     QEX = HEATING OF WORKING GAS IN HEATER TUBES DURING TIME STEP, J
C     QHI(4) = CUMULATIVE HEAT INPUT FOR CYCLE, J
C     QM(7) = HEAT RECEIVED BY METAL NODES 1 TO 7 DURING STEP 5
C     R = 8.314 J/G MOL K
C     RAD = 0.017453 RADIANS/DEGREE
C     RAF = RATIO OF AIR TO FUEL, G/G
C     RA1 = RAF+1, G/G
C     RC = RADIUS OF CRANK, CM
C     RC2 = 2*RC
C     RE = REYNOLDS NUMBER
C     REV = NUMBER OF ENGINE REVOLUTIONS SINCE START
C     RF = ROLLING FRICTION, NEWTONS
C     RGE = WORKING GEAR RATIO, METERS/REV
C     RGE1 = FIRST GEAR RATIO, VEHICLE TRAVEL/REV, METERS
C     RGE2 = SECOND GEAR RATIO, VEHICLE TRAVEL/REV, METERS
C     RGE3 = THIRD GEAR RATIO, VEHICLE TRAVEL/REV, METERS
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C     RM = RESIDUAL MASS IN STEP 4, G
C     RR = RESIDUAL RATIO IN STEP 4
C     RT = INTERFACE TEMPERATURE IN STEP 4
C     RWT = REGENERATOR WALL THICKNESS,CM
C     RX = CP - CV
C     SPM = CRUISING SPEED OF VEHICLE, M/S
C     SPVD = VEHICLE SPEED DESIRED BY SCHEDULE, M/S
C     SPV1 = SPEED OF VEHICLE AT BEGINNING OF TIME STEP, M/SEC
C     SS = CHECK TO ALLOW USER CHANCE TO STOP
C     STN = STANTON NUMBER TIMES PRANDL NUMBER TO TWO THIRDS POWER
C     T1 = AMBIENT AIR TEMPERATURE, K
C     TA = AVERAGE OF HEATER METAL TEMPERATURES, K
C     TAC = VEHICLE ACCELERATION TIME, SEC
C     TAPH = THICKNESS OF PREHEATER PASSAGE, CM
C     TC = GAS TEMPERATURE AT REGENERATOR-COOLER BOUNDARY, K
C     TCR = DURATION OF STARTING MOTOR TORQUE, SEC
C     TCY = THICKNESS OF CYLINDER WALL, CM
C     TD = THMG-TWI
C     TE = ERROR IN CONTROLLED TEMP. OF HOT METAL, K
C     TG(X,Y,Z) = MATRIX OF GAS TEMPERATURES AT NODE BOUNDARIES
C        X=1 BEFORE MASS FLOW =2 AFTER
C        Y=1 MIXED TEMP OF ADIABATIC HOT SPACES
C        Y=2 AT HOT END OF HEATER MANIFOLD
C        Y=3 AT INTERFACE BETWEEN HEATER MANIFOLD AND HEATER
C        Y=4 AT INTERFACE BETWEEN HEATER AND REGENERATOR MANIFOLD
C        Y=5 AT INTERFACE BETWEEN REGEN. MAN. AND REGENERATOR
C        Y=6 AT MIDPOINT IN REGENERATOR
C        Y=7 IN COOLER
C        Y=8 IN ADIABATIC COLD SPACE
C        Z=1 TO 4 FOR 4 WORKING SPACES
C     TGA(X,Y,Z) = MATRIX OF AVERAGE GAS TEMPERATURES
C        X=1 BEFORE MASS FLOW =2 AFTER
C        Y=1 FOR HOT SPACES
C        Y=2 FOR HEATER MANIFOLDS
C        Y=3 FOR HEATERS
C        Y=4 FOR REGENERATOR MANIFOLDS
C        Y=5 FOR HOT HALF OF REGENERATOR
C        Y=6 FOR COLD HALF OF REGENERATOR
C        Y=7 FOR COOLER
C        Y=8 FOR COLD SPACES
C        Z=1,4 FOR 4 WORKING SPACES
C     TH = GAS TEMP. AT REGEN. MANIFOLD-REGENERATOR BOUNDARY, K
C     THC = THICKNESS OF HOT CAP CYLINDER, CM
C     THCH = THICKNESS OF HOT CAP HEAD, CM
C     THH = THICKNESS OF HOT CYLINDER WALL HEAD, CM
C     THW = THICKNESS OF WIRE IN SCREENS OF REGENERATOR, CM
C     THMG = TEMPERATURE, HOT METAL GOAL, K
C     THU = ENGINE WARM-UP TIME, SEC
C     TID = IDLE TIME AFTER CRANKING, SEC
C     TI1 = THU+TCR
C     TI2 = TI1+TID
C     TI3 = TI2+TAC
C     TIM = CUMULATIVE TIME, SEC
C     TIMX = SPECIFIC CUMULATIVE TIME FLAG, SEC
C     TIN(20) = INLET AIR PREHEATER AIR NODE TEMP., K
C     TM(1,Y) = METAL TEMP. AROUND HOT SPACE, K
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C     TM(2,Y) = METAL TEMP. BETWEEN HEATER MAN. AND HEATER, K
C     TM(3,Y) = METAL TEMP. BETWEEN HEATER AND REGEN. MAN., K
C     TM(4,Y) = METAL TEMP. BETWEEN REGEN. MAN. AND REGEN., K
C     TM(5,Y) = METAL TEMP. MIDPOINT OF REGENERATOR, K
C     TM(6,Y) = METAL TEMP. BETWEEN REGEN. AND COOLER, K
C     TM(7,Y) = METAL TEMP. BETWEEN COOLER AND COLD SPACE, K
C     TMAPH = THICKNESS OF METAL SEPARATING EACH FLOW PASSAGE, CM
C     TNET = NET ENGINE TORQUE, N-M
C     TOTT = TOTAL SIMULATION TIME, SEC
C     TOU(20) = AIR PREHEATER FLUE GAS NODE TEMP., K
C     TPB = TEMPERATURE, PROPORTIONAL BAND IN HOT METAL, K
C     TQ(4) = TORQUE FROM EACH PISTON, CCW IS POSITIVE, N-M
C     TQI = TOTAL INDICATED TORQUE, N-M
C     TQS = TOTAL SHAFT TORQUE, N-M
C     TQV = TORQUE VEHICLE PUTS ON ENGINE, N-M
C     TRAV = AVERAGE REG. METAL TEMP, K
C     TREP = TIME INTERVAL FOR REPORT PRINTOUT, SEC
C     TRH = THICKNESS OF REGENERATOR HEAD, CM
C     TST = STARTING MOTOR TORQUE, N-M
C     TT = CHECK TO DETERMINE WHEN POINTS SHOULD BE PLOTTED
C     TWI = TEMPERATURE, WATER INLET, K
C     TWO = TEMPERATURE OF COOLING WATER, K
C     TXM1 = TEMP-MASS PRODUCT FOR GAS MOVING PAST NODE 1
C     TXM2 TO TXM6 = SAME FOR NODES 2 TO 6
C     UAPH = HEAT TRANSFER COEFF. AIR TO METAL IN AIR PREHEATER, W/CM2 K
C     UH = HEAT TRANSFER COEFF. FLUE GAS TO GAS HEATER METAL, W/CM2 K
C     UXX = LAPH*WAPH*2.*NAPH/(4.*RAF*CPA)
C     UXY = LAPH*WAPH*2.*NAPH/(4.*CZ)
C     V1 = VOLUME OF GAS MOVED TOWARD COLD END AT NODE 1, CM2
C     V2 TO V7 = SAME FOR NODES 2 TO 7
C     VAB = VOLUME OF AIR IN BURNER, CU CM
C     VCA(2,4) = VOLUME, COLD, ADIABATIC, START AND END OF TIME STEP
C     VCA1(4) = VOLUMES OF GAS ORIGINALLY IN ADIABATIC COLD SPACE
C               AFTER VOLUME CHANGE, CU CM
C     VCDA = VOLUME, ADIABATIC COLD DEAD, CU CM
C     VCD = VOLUME, ISOTHERMAL COLD DEAD, CU CM
C     VCD(4) = VOLUMES OF GAS ORIGINALLY IN GAS COOLER AND
C                ISOTHERMAL PART OF COLD DUCT AFTER VOLUME CHANGE
C     VCDX = VOLUME, COLD DEAD NOT IN GAS COOLER, CU CM
C     VHA(2,4) = VOLUME, HOT, ADIABATIC,START AND END OF TIME STEP
C     VHA1(4) = VOLUMES OF GAS ORIGINALLY IN HOT ADIABATIC SPACE
C               AFTER VOLUME CHANGE, CU CM
C     VHD = HEATER DEAD VOLUME, (ASSUMED ISOTHERMAL) CU CM
C     VHD1(4) = VOLUMES OF GAS ORIGINALLY IN HOT DEAD SPACE AFTER
C               VOLUME CHANGE, CU CM
C     VHDX = EXTRA HOT VOLUME BESIDES THAT IN THE GAS HEATER,
C            CU CM, INCLUDES END CLEARANCE, GAP AROUND HOT CAP
C            AND MANIFOLD ASSUMED ADIABATIC
C     VHM = HEATER MANIFOLD DEAD VOLUME, CU CM
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C     VIN = VEHICLE INERTIA AS SEEN AT CRANK SHAFT, KG*M**2
C     VRD = VOLUME, REGENERATOR DEAD, PER CYLINDER, CU CM
C     VRD1(4) = VOLUMES OF GAS ORIGINALLY IN REGENERATOR AFTER VOLUME
C              CHANGE, CU CM
C     VRM = REGENERATOR MANIFOLD DEAD VOLUME, CU CM
C     VSP2 = VEHICLE SPEED TO CHANGE TO SECOND GEAR, M/SEC
C     VSP3 = VEHICLE SPEED TO CHANGE TO THIRD GEAR, M/SEC
C     VT(2,4) = TOTAL GAS VOLUMES AT START AND END OF TIME STEP, CU CM
C     VTD = TOTAL DEAD VOLUME, CU CM
C     W(X,Y,Z) = ARRAY OF NODAL GAS MASSES
C        X=1 BEFORE MASS FLOW =2 AFTER
C        Y=1 ADIABATIC HOT SPACES
C        Y=2 HEATER MANIFOLDS
C        Y=3 HEATERS
C        Y=4 REGENERATOR MANIFOLDS
C        Y=5 HOT HALF OF REGENERATORS
C        Y=6 COLD HALF OF REGENERATORS
C        Y=7 COOLERS
C        Y=8 ADIABATIC COLD SPACES
C        Z=1,4 FOR 4 WORKING SPACES
C     WAPH = WIDTH OF EACH AIR PREHEATER PASSAGE, CM
C     WRC = MASS OF REGENERATOR GAS MOVING INTO COOLER, G
C     WRH = MASS OF REGENERATOR GAS MOVING INTO HEATER, G
C     WTHM = WALL THICKNESS OF TUBES IN HEATER MAN.,CM
C     WTRM = WALL THICKNESS OF TUBES IN REGEN. MAN.,CM
C     X = TEMPORARY VARIABLE
C     X1 = ENGINE SPACINGS IN 4 CYLINDER MACHINE
C     X2 =   "       "       "  "     "        "
C     X3 =   "       "
C     X4 =   "       "
C     X9 = EXP(UXX/CYY), ZERO FOR SLOW AIR FLOW THROUGH PREHEATER
C     XA = LCR**2
C     XB = LCR - RC
C     XC = R / MW
C     XDV = HORIZONTAL SCALE FACTOR FOR PV PLOT, CM**3
C     XH = HEAT TRANSFER FACTOR FOR GAS HEATERS
C     XLOW = HORIZ. ZERO SURPRESSOR FOR PV PLOT, CM**3
C     XX(4) = OLD, NEW VOLUME RATIO
C     XT(4) = OLD, NEW TEMPERATURE RATIO
C     XY = HEAT TRANSFER FACTOR FOR AIR SIDE OF APH
C     XZ = HEAT TRANSFER FACTOR FOR FLUE GAS SIDE OF APH
C     Y = TEMPORARY VARIABLE
C     YY = TEMPORARY VARIABLE
C     Z = FLAG FOR WORKING FLUID, 1 FOR H2, 2 FOR HE, 3 FOR AIR
C     ZZ = TEMPORARY VARIABLE
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C        ***** START OF PROGRAM *****
         DIMENSION THM(4),TCM(4),TGHS(2,4),TGH(2,4),TGC(2,4),TGCS(2,4),
     1   P2(4),P3(4,5),P4(4),M(4),FP(4),TQ(4),VHA(2,4),VCA(2,4),
     2   VCA1(4),VCD1(4),VHA1(4),VHD1(4),VRD1(4),VT(2,4),XX(4),
     3   WHA(2,4),WHD(2,4),WRD(2,4),WCD(2,4),WCA(2,4),TGR(2,4),P1(4),
     4   TMR(4),QHI(4),T3A(4),CM(6),KME(6)
         INTEGER Z
         REAL LCR,LH,LR,MSH,MW,KK,KR,LC,M,ME,KRR,KAR,MGI
         REAL LHH,LHV,MWFG,LAPH,MIR,MIR1,LHM,MIV,LRM,KM,KMX
         REAL NTRM,NTC,NS,NR,NTH,NTHM,IG1,NO,NAPH,KAPH,KME
C  BASE CASE INPUT IN ORDER OF CHANGE TABLE
         DATA THMG,TPB,TWI,FWI,OM1/922.2,50.,300.,1575.,40./
         DATA T1,DT,ME,Z,RGE1/300.,.5,90.,1,0.54/
         DATA NTHM,DIHM,FFF,THU,LHM/36.,0.472,4.85,20.,7.95/
         DATA TCR,TID,TAC,TOTT,SPM/1.0,1.0,30.,90.,22.4/
         DATA RC,LCR,DCY,DDR,DIH/2.325,13.65,10.16,4.06,0.472/
         DATA WTHM,NTH,VHDX,NR,DR/0.084,36.,11.59,6.,3.5/
         DATA LR,FF,NS,MSH,THW/2.5,0.2,0.,0.0,0.0/
         DATA VCDX,FCA,DIC,LC,NTC/196.02,0.95,0.115,12.9,312./
         DATA MIV,NTRM,DIRM,AFR,LRM/1100.,36.,.472,1.12,7.95/
         DATA DOH,LHH,TMAPH,LAPH,WAPH/0.640,25.58,0.01,10.,5./
         DATA TAPH,NAPH,PRL,PRH,WTRM/0.3,50.,.5,10.,0.084/
         DATA TST,MIR,RAF,NO,LHV/1000.,150.,16.55,8.,46.432/
         DATA GCT,RGE2,RGE3,VSP2,VSP3/1.0,1.0,2.0,4.47,13.42/
         DATA THH,TRH,RWT,TCY,THC/1.5,0.5,0.41,1.27,0.381/
         DATA G,HCL,KM,KMX,THCH/0.0406,10.03,0.2,0.017,0.381/
         DATA Q1,Q2,Q3,EIN,PBIS/1.,2.,1.,50.0,5.0/
         DATA PBVS,TREP/1.0,5.0/
C DATA CONSTANTS
         DATA PI4,PI,PI2,RAD,R/0.7854,3.14159,1.57080,0.917453,8.314/
         DATA J,CPA,CPFG/5,1.03,1.20/
         WRITE(J,8006)
 8006    FORMAT(' DATA READ IN')
C  INSTALL BASE CASE DATA OR DATA FROM FORT10.DAT
         WRITE(5,8010)
 8010    FORMAT(' TYPE 1 LEAVE IN BASE CASE DATA'/
     1'  TYPE 2 TO BRING IN STORED DATA FROM LAST CASE.')
         READ(5,8011)I
 8011    FORMAT(I3)
         IF(I-2)950,960,960
C READ IN DATA FROM LAST CASE
 960     READ(10,8004)THMG,TPB,TWI,FWI,OM1
         READ(10,8004)T1,DT,ME,RGE1,KAPH
         READ(10,8004)NTHM,DIHM,FFF,THU,LHM
         READ(10,8004)TCR,TID,TAC,TOTT,SPM
         READ(10,8004)RC,LCR,DCY,DDR,DIH
         READ(10,8004)WTHM,NTH,VHDX,NR,DR
         READ(10,8004)LR,FF,NS,MSH,THW
         READ(10,8004)VCDX,FCA,DIC,LC,NTC
         READ(10,8004)MIV,NTRM,DIRM,AFR,LRM
         READ(10,8004)DOH,LHH,TMAPH,LAPH,WAPH
         READ(10,8004)TAPH,NAPH,PRL,PRH,WTRM
         READ(10,8004)TST,MIR,RAF,NO,LHV
         READ(10,8004)CMAPH,AFAPH,RA1,CZ,DEQ
         READ(10,8004)UXY,DT2,CY,UXX,CYY
         READ(10,8004)FUEL,AMF,AH,CMH,QEX
         READ(10,8004)KAR,TIM,VHD,VRD,CMX
         READ(10,8004)VCD,VCDA,VTD,XA,XB
         READ(10,8004)ACY,BCY,PI32,RC2,CCY
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      READ(10,8004)EARAD,EADEG,DIST,UMEG,GCT
      READ(10,8004)VHA(1,1),VHA(1,2),VHA(1,3),VHA(1,4),VCA(1,1)
      READ(10,8004)VCA(1,2),VCA(1,3),VCA(1,4),VT(1,1),VT(1,2)
      READ(10,8004)VT(1,3),VT(1,4),CP,CV,MW
      READ(10,8004)RX,KK,GA,KR,XC
      READ(10,8004)TOV,IG1,VHM,VRM,RGE2
      READ(10,8004)RGE3,VSP2,VSP3,THH,TRH
      READ(10,8004)RWT,TCY,THC,G,HCL
      READ(10,8004)KM,KMX,THCH,Q1,Q2
      READ(10,8004)Q3,EIN,KME(1),KME(2),KME(3)
      READ(10,8004)KME(4),KME(5),KME(6),CM(1),CM(2)
      READ(10,8004)CM(3),CM(4),CM(5),PBIS,PBVS
      READ(10,8004)TREP
      ENDFILE 10
      WRITE(5,8005)Q1
8005  FORMAT(' OLD DATA READ IN!  Q1=',F8.2)
950   WRITE(5,5)
5     FORMAT(' CNTLA INPUT ADJUSTMENT PROGRAM   TO CHANGE '/
     1' TYPE 2 DIGIT INPUT NUMBER A SPACE, AND THE NEW INPUT VALUE'/
     2' WITH A DECIMAL POINT   TO CONTINUE HIT RETURN'/)
      READ(5,7)I
7     FORMAT(I1)
9     WRITE(J,10)
10    FORMAT(///////'0',71('*')/' * OPERATING CONDITIONS BY NUMBER'
     1,10X,'*',13X,'*',13X,'*')
      WRITE(J,12)THMG,TPB,TWI,FWI,OM1,T1,DT,ME,Z,RGE1
12    FORMAT(' * 01',F9.3,' * 02',F9.3,' * 03',F9.3,' * 04',F9.3,
     1 ' * 05',F9.3,' *'/' * 06',F9.3,' * 07',F9.3,' * 08',F9.3,' * 09',
     2 I5,'      * 10',F9.3,' *')
      WRITE(J,14)NTHM,DIHM,FFF,THU,LHM,TCR,TID,TAC,TOTT,SPM
C----+----1----+----2----+----3----+----4----+----5----+----6----+----712
14    FORMAT(' * 11',F9.3,' * 12',F9.3,' * 13',F9.3,' * 14',F9.3,
     1 ' * 15',F9.3,' *'/' * 16',F9.3,' * 17',F9.3,' * 18',F9.3,' * 19'
     2 ,F9.3,' * 20',F9.3,' *')
      WRITE(J,20)RC,LCR,DCY,DDR,DIH,WTHM,NTH,VHDX,NR,DR
20    FORMAT(
     1' * 21',F9.3,' * 22',F9.3,' * 23',F9.3,' * 24',F9.3,' * 25',F9.3,
     2' *'/' * 26',F9.3,' * 27',F9.3,' * 28',F9.3,' * 29',F9.3,' * 30'
     3,F9.3,' *')
      WRITE(J,22)LR,FF,NS,MSH,THW,VCDX,FCA,DIC,LC,NTC
22    FORMAT(' * 31',F9.3,' * 32',F9.3,' * 33',F9.3,' * 34',F9.3,
     1' * 35',F9.3,' *'/' * 36',F9.3,' * 37',F9.3,' * 38',F9.3,' * 39',
     2 F9.3,' * 40',F9.3,' *')
      WRITE(J,25)MIV,NTRM,DIRM,AFR,LRM,DOH,LHH,TMAPH,LAPH,NAPH
25    FORMAT(' * 41',F9.3,' * 42',F9.3,' * 43',F9.3,' * 44',F9.3
     1 ' * 45',F9.3,' *'/' * 46',F9.3,' * 47',F9.3,' * 48',F9.3,
     2 ' * 49',F9.3,' * 50',F9.3,' *')
      WRITE(J,26)TAPH,NAPH,PRL,PRH,WTRM,TST,MIR,RAF,NO,LHV
26    FORMAT(' * 51',F9.3,' * 52',F9.3,' * 53',F9.3,' * 54',F9.3,
     1 ' * 55',F9.3,' *'/' * 56',F9.3,' * 57',F9.3,' * 58',F9.3,' * 59',
     2 F9.3,' * 60',F9.3,' *')
      WRITE(J,27)GCT,RGE2,RGE3,VSP2,VSP3,THH,TRH,RWT,TCY,THC
27    FORMAT(' * 61',F9.3,' * 62',F9.3,' * 63',F9.3,' * 64',F9.3
     1 ' * 65',F9.3,' *'/' * 66',F9.3,' * 67',F9.3,' * 68',F9.3,' * 69'
     2 F9.3,' * 70',F9.3,' *')
      WRITE(J,29)G,HCL,KM,KMX,THCH,Q1,Q2,Q3,EIN,PBIS
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ORIGINAL PAGE IS
OF POOR QUALITY

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   29     FORMAT(' * 71',F9.3,' * 72',F9.3,' * 73',F9.3,' * 74',F9.3,
        1 ' * 75',F9.3,' *'/' * 76',F9.3,' * 77',F9.3,' * 78',F9.3,
        2 ' * 79',F9.3,' * 80',F9.3,' *')
          WRITE(J,30)PBVS,TREP
   30     FORMAT(' * 81',F9.3,' * 82',F9.3,' * 83',F9.3,' * 84',F9.3,
        1 ' * 85',F9.3,' *'/' * 86',F9.3,' * 87',F9.3,' * 88',F9.3,
        2 ' * 89',F9.3,' * 90',F9.3,' *')
          WRITE(J,28)
   28     FORMAT(' ',71('*')/' II XXXXXXXXX',2X,'TYPE 99 TO CALCULATE'
        1 'AND FILE INTERMEDIATE VALUES'/)
          READ(5,36)I7,OO
   36     FORMAT(I2,1X,F10.2)
          IF(I7.EQ.99) GO TO 140
          IF(I7-9)45,45,38
   38     IF(I7-19)47,47,39
   39     IF(I7-29)49,49,40
   40     IF(I7-39)50,50,41
   41     IF(I7-49)51,51,42
   42     IF(I7-59)52,52,43
   43     IF(I7-69)120,120,121
  121     IF(I7-79)150,150,151
  151     IF(I7-89)190,190,191
  191     GOTO9
   45     GO TO (53,54,55,56,57,58,59,60,61),I7
   47     I7=I7-9
          GO TO (62,63,64,65,66,67,68,69,70,71),I7
   49     I7=I7-19
          GO TO (72,73,74,75,76,77,78,79,80,81),I7
   50     I7=I7-29
          GO TO (82,83,84,85,86,87,88,89,90,91),I7
   51     I7=I7-39
          GO TO (92,93,94,95,96,97,98,99,100,101),I7
   52     I7=I7-49
          GO TO (102,103,104,105,106,107,108,109,110,111),I7
  120     I7=I7-59
          GO TO (122,123,124,125,126,127,128,129,130,131),I7
  150     I7=I7-69
          GO TO (152,153,154,155,156,157,158,159,160,161),I7
  190     I7=I7-79
          GO TO (192,193,194,195,196,197,198,199,200,201),I7
   53     THMG=OO
          GOTO9
   54     TPB=OO
          GOTO9
   55     TWJ=OO
          GOTO9
   56     FWI=OO
          GOTO9
   57     OM1=OO
          GOTO9
   58     T1=OO
          GOTO9
   59     DT=OO
          GOTO9
   60     ME=OO
          GOTO9
```

```
61      Z=QQ
        GOTO9
62      RGE1=QQ
        GOTO9
63      NTHM=QQ
        GOTO9
64      DIHM=QQ
        GOTO9
65      FFF=QQ
        GOTO9
66      THU=QQ
        GOTO9
67      LHM=QQ
        GOTO9
68      TCR=QQ
        GOTO9
69      TID=QQ
        GOTO9
70      TAC=QQ
        GOTO9
71      TOTT=QQ
        GOTO9
72      SPM=QQ
        GOTO9
73      RC=QQ
        GOTO9
74      LCR=QQ
        GOTO9
75      DCY=QQ
        GOTO9
76      DDR=QQ
        GOTO9
77      DIH=QQ
        GOTO9
78      WTHM=QQ
        GOTO9
79      NTH=QQ
        GOTO9
80      VHDX=QQ
        GOTO9
81      NR=QQ
        GOTO9
82      DR=QQ
        GOTO9
83      LR=QQ
        GOTO9
84      FF=QQ
        GOTO9
85      NS=QQ
        GOTO9
86      MSH=QQ
        GOTO9
87      THW=QQ
        GOTO9
88      VCDX=QQ
        GOTO9
89      FCA=QQ
        GOTO9
90      DIC=QQ
        GOTO9
91      LC=QQ
        GOTO9
92      NTC=QQ
        GOTO9
93      MIV=QQ
        GOTO9
94      NTRM=QQ
        GOTO9
95      DIRM=QQ
        GOTO9
96      AFR=QQ
        GOTO9
97      LRM=QQ
        GOTO9
98      DOH=QQ
        GOTO9
99      LHH=QQ
        GOTO9
100     TMAPH=QQ
        GOTO9
101     LAPH=QQ
        GOTO9
102     WAPH=QQ
        GOTO9
103     TAPH=QQ
        GOTO9
104     NAPH=QQ
        GOTO9
105     PRL=QQ
        GOTO9
106     PRH=QQ
        GOTO9
107     WTRM=QQ
        GOTO9
108     TST=QQ
        GOTO9
109     MIR=QQ
        GOTO9
110     RAF=QQ
```

```
C  NUMBER OF NODES IN APH FIXED BECAUSE OF PROGRAM SIZE
         GOTO9
  111    NO=8
         GOTO9
  122    LHV=00
         GOTO9
  123    GCT=00
         GOTO9
  124    PGEI=00
         GOTO9
  125    PGEO=00
         GOTO9
  126    VFRI=00
         GOTO9
  127    VSRI=00
         GOTO9
  128    THH=00
         GOTO9
  129    TRH=00
         GOTO9
  130    RWT=00
         GOTO9
  131    TCY=00
         GOTO9
  152    THC=00
         GOTO9
  153    G=00
         GOTO9
  154    HCL=00
         GOTO9
  155    KM=00
         GOTO9
  156    KMX=00
         GOTO9
  157    THCH=00
         GOTO9
  158    O1=00
         GOTO9
  159    O2=00
         GOTO9
  160    O3=00
         GOTO9
  161    EIN=00
         GOTO9
  192    PBIS=00
         GOTO9
  193    PBVS=00
         GOTO9
  194    TREP=00
         GOTO9
  195    GOTO9
  196    GOTO9
  197    GOTO9
  198    GOTO9
  199    GOTO9
  200    GOTO9
  201    GOTO9
```

```
C   HEAT CAPACITY OF AIR PREHEATER METAL ASSUMING STEEL WITH
C   5.00 J/CU CM K HEAT CAPACITY
140     CMAPH=LAPH*WAPH*2.*NAPH*TMAPH*5.00/NO
C  HEAT CAPACITY OF ENGINE METAL NODES
        X=PI4*DCY**2.*(THH+THCH)
        Y=PI*DCY*(TCY+THC)*HCL/2.
        ZZ=PI*DIHM*WTHM*NTHM*LHM/2.
        CM(1)=(X+Y+ZZ)*5.00
        X=PI4*(DOH**2.-DIH**2.)*NTH*LHH/2.
        CM(2)=(ZZ+X)*5.00
        Y=PI*DIRM*WTRM*NTRM*LRM/2.
        CM(3)=(X+Y)*5.00
        X=PI4*(DR+RWT)**2.*TRH*NR
        ZZ=PI*DR*RWT*LR/4.+PI4*DR**2.*LR/4*FF
        CM(4)=(Y+X+ZZ)*5.00
        CM(5)=2.*ZZ*5.00
C   FLOW AREA IN PREHEATER
        AFAPH=WAPH*TAPH*NAPH
C   HEAT TRANSFER CONSTANTS
        RA1=RAF+1
        CZ=CPFG*RA1
        DEQ=2.*WAPH*TAPH/(WAPH+TAPH)
        UXY=LAPH*WAPH*2.*NAPH/(NO*CZ)
        DT2=LHV*1000./CZ
        CY=CPA*RAF*4./CMAPH
        UXX=LAPH*WAPH*2.*NAPH/(NO*RAF*CPA)
        CYY=CZ*4./CMAPH
        FUEL=0.
C   MINIMUM FLOW AREA FOR FLUE GAS THROUGH GAS HEATER
        AMF=DOH*LHH*NTH/2.
C  HEAT TRANSFER AREA GAS HEATER FOR ONE CYLINDER
        AH=PI*DOH*LHH*NTH
C  HEAT CAPACITY OF GAS HEATER FOR ONE CYLINDER
        CMH=4.71*PI4*(DOH**2-DIH**2)*LHH*NTH
C  INIALIZATIONS
        OEX=0
        JH=1
        TIM=0
C  HEATER MANIFOLD DEAD VOLUME, VHM
        VHM=PI4*DIHM**2*LHM*NTHM
C  HOT DEAD VOLUME PER CYLINDER, VHD
167     VHD=PI4*DIH**2*LHH*NTH
C  REGENERATOR MANIFOLD DEAD VOLUME, VRM
        VRM=PI4*DIRM**2*LRM*NTRM
C  REGENERATOR DEAD VOLUME AND HEAT CAPACITY PER CYLINDER, VRD,CMX
        IF(FF) 168,171,172
168     WRITE(5,169)
169     FORMAT(' INPUT DATA ERROR, PRESS ENTER TO RETURN TO MENU')
        READ(5,170)X
170     FORMAT(I3)
        GOTO9
171     VRD=NR*PI4*DR**2*(LR-2*PI4*NS*MSH*THW**2)
        CMX=4.71*NR*PI4*DR**2*LR*MSH*PI4*THW
        X=NR*DR**2*LR
        FF=(X-VRD)/X
        GOTO173
172     VRD=NR*PI4*DR**2*LR*(1.-FF)
        CMX=4.71*NR*PI4*DR**2*LR*FF
173     CONTINUE
```

```
C   COOLER DEAD VOLUME PER CYLINDER
C   ISOTHERMAL
          VCD=VCDX*(1.-FCA)+PI4*DIC**2*LC*NTC
C   ADIABATIC
          VCDA=VCDX*FCA
C   TOTAL DEAD VOLUME
          VTD=VHM+VHD+VRM+VRD+VCD
C   INTERMEDIATE VALUES TO MAKE ENGINE VOLUMES CALCULATE FASTER
          XA=LCR**2
          XB=LCR-RC
          ACY=PI4*DCY**2
          BCY=PI4*(DCY**2-DDR**2)
          PI32=3.*PI/2
          RC2=2*RC
          CCY=ACY-BCY
C   SET INITIAL SPEED, ANGLE, DISTANCE
          EARAD=0
          EADEG=0
          DIST=0
          OMEG=0
C   CALCULATE AIR RESISTANCE CONSTANT
          KAR=0.5990*AFR
C   SET INITIAL ENGINE VOLUMES
          X1=SQRT(XA-(RC*SIN(EARAD))**2)-RC*COS(EARAD)-XB
          X2=SQRT(XA-(RC*SIN(EARAD+PI2))**2)-RC*COS(EARAD+PI2)-XB
          X3=SQRT(XA-(RC*SIN(EARAD+PI))**2)-RC*COS(EARAD+PI)-XB
          X4=SQRT(XA-(RC*SIN(EARAD+PI32))**2)-RC*COS(EARAD+PI32)-XB
          VHA(1,1)=ACY*(RC2-X1)+VHDX
          VCA(1,1)=BCY*X2+VCDA
          VHA(1,2)=ACY*(RC2-X2)+VHDX
          VCA(1,2)=BCY*X3+VCDA
          VHA(1,3)=ACY*(RC2-X3)+VHDX
          VCA(1,3)=BCY*X4+VCDA
          VHA(1,4)=ACY*(RC2-X4)+VHDX
          VCA(1,4)=BCY*X1+VCDA
          DO 174 I=1,4
 174      VT(1,I)=VTD+VHA(1,I)+VCA(1,I)
C   SET WORKING GAS PROPERTIES
          GO TO (176,177,178),Z
 176      CP=14.52
          CV=10.39
          MW=2.02
          GOTO179
 177      CP=5.2
          CV=3.12
          MW=4.0
          GOTO179
 178      CP=1.029
          CV=0.7426
          MW=29.0
 179      CONTINUE
C   GAS QUANTITIES
          RX=CP-CV
          KK=CP/CV
          GA=(KK-1.)/KK
          KR=1./KK
          XC=R/MW
          TOV=0
          IG1=0
```

```
C THERMAL CONDUCTANCE BETWEEN APH METAL NODES
        KAPH=KM*TMAPH*WAPH*NAPH*2.*NO/LAPH
C THERMAL CONDUCTANCE BETWEEN ENGINE METAL NODES
        KME(1)=KM*PI*DCY*(TCY+THC)/HCL
        KME(2)=KM*PI*DIHM*WTHM*NTHM/LHM
        KME(3)=KM*PI4*(DOH**2-DIH**2)*NTH/LHH
        KME(4)=KM*PI*DIRM*WTRM*NTRM/LRM
        KME(5)=KM*PI*DR*RWT*NR/(LR/2.)+KMX*PI4*DR**2*NR/(LR/2.)
        KME(6)=KME(5)
C WRITE TRANSFER FILE TO DISK
8004    FORMAT(5(F9.3))
        WRITE(10,8004)THMG,TPB,TWI,FWI,OM1
        WRITE(10,8004)T1,DT,ME,RGE1,KAPH
        WRITE(10,8004)NTHM,DIHM,FFF,THU,LHM
        WRITE(10,8004)TCR,TID,TAC,TOTT,SPM
        WRITE(10,8004)RC,LCR,DCY,DDR,DIH
        WRITE(10,8004)WTHM,NTH,VHDX,NR,DR
        WRITE(10,8004)LR,FF,NS,MSH,THW
        WRITE(10,8004)VCDX,FCA,DIC,LC,NTC
        WRITE(10,8004)MIV,NTRM,DIRM,AFR,LRM
        WRITE(10,8004)DOH,LHH,TMAPH,LAPH,WAPH
        WRITE(10,8004)TAPH,NAPH,PRL,PRH,WTRM
        WRITE(10,8004)TST,MIR,RAF,NO,LHV
        WRITE(10,8004)CMAPH,AFAPH,RA1,CZ,DEQ
        WRITE(10,8004)UXY,DT2,CY,UXX,CYY
        WRITE(10,8004)FUEL,AMF,AH,CMH,QEX
        WRITE(10,8004)KAR,TIM,VHD,VRD,CMX
        WRITE(10,8004)VCD,VCDA,VTD,XA,XB
        WRITE(10,8004)ACY,BCY,PI32,RC2,CCY
        WRITE(10,8004)EARAD,EADEG,DIST,OMEG,GCT
        WRITE(10,8004)VHA(1,1),VHA(1,2),VHA(1,3),VHA(1,4),VCA(1,1)
        WRITE(10,8004)VCA(1,2),VCA(1,3),VCA(1,4),VT(1,1),VT(1,2)
        WRITE(10,8004)VT(1,3),VT(1,4),CP,CV,MW
        WRITE(10,8004)RX,KK,GA,KR,XC
        WRITE(10,8004)TQV,IG1,VHM,VRM,RGE2
        WRITE(10,8004)RGE3,VSP2,VSP3,THH,TRH
        WRITE(10,8004)RWT,TCY,THC,G,HCL
        WRITE(10,8004)KM,KMX,THCH,Q1,Q2
        WRITE(10,8004)Q3,EIN,KME(1),KME(2),KME(3)
        WRITE(10,8004)KME(4),KME(5),KME(6),CM(1),CM(2)
        WRITE(10,8004)CM(3),CM(4),CM(5),PBIS,PBVS
        WRITE(10,8004)TREP
5000    STOP
        END
```

FORTRAN SOURCE CODE LISTING

OF CNTLB

```
C ************PROGRAM CNTLB FOR*****************************
C WRITTEN BY MARTINI ENGINEERING UNDER CONTRACT NUMBER
C DEN3-226 FOR NASA-LEWIS UNDER THE DOE ADVANCED AUTOMOTIVE
C PROPULSION PROGRAM   CNTLB READS IN THE INPUT DATA FILE
C GENERATED IN CNTLA AND CALCULATES AND DISPLAYS RESULTS
C CNTLB CALCULATES THE TRANSIENT PERFORMANCE OF A 4 CYLINDER
C DOUBLE ACTING STIRLING ENGINE WITH TUBULAR HEAT EXCHANGERS
C AND POROUS REGENERATOR CONNECTED TO A VEHICLE THROUGH A GEAR BOX
C THE RESIDENT DRIVING CYCLE CONSISTS OF HEATUP,CRANKING,IDLE,
C ACCELERATION FROM ZERO TO CRUSE SPEED AND HOLD THAT SPEED
C SECOND AND THIRD GEAR CHANGES ARE SPECIFIED BASED UPON VEHICLE
C SPEED  GEAR CHANGE IS LINEAR WITH A SPECIFIED TIME
C CNTLA USES AS A BASE CASE THE DIMENSIONS OF THE 4L23 ENGINE
C CNTLB ADJUSTS THE TIME STEP SO THAT THE ANGLE INCREMENT IS
C BETWEEN 7 AND 30 DEGREES  THE PROGRAM HAS NO LIMIT TO FLOW
C ACROSS GAS NODES OR CHANGE IN GAS INVENTORY  CONTROL IS BY
C CHANGE IN GAS INVENTORY.
C         ***** START OF PROGRAM *****
          DIMENSION XT(4),IPV(2,4),JPV(2,4),
      1   P2(4),P3(4,8),P4(4),M(4),FR(4),TO(4),VHA(2,4),VCA(2,4),
      2   VT(2,4),XX(4),
      3   P1(4),CVM(8,4),TGA(2,8,4),
      4   OHI(4),TIA(4),TIN(10),EX(8),TOU(10),TM(6,4),EY(8),KME(8),
      5   OM(8),TMA(8,4),
      6   CM(5)
          DIMENSION TM1(6,4),W(2,8,4),CVG(8,4)
          REAL LCR,LH,LR,MSH,MW,KK,KR,LC,M,ME,KAR,MGI
          REAL LHH,LHV,MWFG,LAPH,MIR,MIR1,LHM,MIV,LRM,M2,MC
          REAL NTRM,NTC,NS,NR,NTH,NTHM,IG1,NO,NAPH,KAPH,KM,KMX,KME
C   DATA CONSTANTS
          DATA PI4,PI,PI2,RAD,R/0.7854,3.14159,1.57080,0.017453,8.314/
          DATA J,CPA,CPFG/5,1.03,1.20/
C****** READ TRANSFER FILE FROM DISK
8004      FORMAT(5,F9.3)
          READ (10,8004)THMG,TRB,TWI,FWI,OM1
          READ (10,8004)T1,DT,MF,RGE1,KAPH
          READ (10,8004)NTHM,DIHM,FFF,THU,LHM
          READ (10,8004)TCR,TID,TAC,TOTT,SPM
          READ (10,8004)RC,LCR,DCY,DDR,DIH
          READ (10,8004)WTHM,NTH,VHDX,NR,DR
          READ (10,8004)LR,FF,NS,MSH,THW
          READ (10,8004)VCDX,FCA,DIC,LC,NTC
          READ (10,8004)MIV,NTRM,DIRM,AFR,LRM
          READ (10,8004)DOH,LHH,TMAPH,LAPH,WAPH
          READ (10,8004)TAPH,NAPH,PPL,PPH,WTRM
          READ (10,8004)TST,MIR,RAF,NO,LHV
          READ (10,8004)CMAPH,AFAPH,RA1,CZ,DEO
          READ (10,8004)UXY,DT2,CY,UXX,CYY
          READ (10,8004)FUEL,AMF,AH,CMH,OEX
          READ (10,8004)KAR,TIM,VHD,VRD,CMX
          READ (10,8004)VCD,VCDA,VTD,XA,XB
          READ (10,8004)ACY,BCY,PI32,RC2,CCY
          READ (10,8004)EARAD,EADEG,DIST,OMEG,GCT
          READ (10,8004)VHA(1,1),VHA(1,2),VHA(1,3),VHA(1,4),VCA(1,1)
```

```
      READ (10,8004)VCA(1,2),VCA(1,3),VCA(1,4),VT(1,1),VT(1,2)
      READ (10,8004)VT(1,3),VT(1,4),CP,CV,MW
      READ (10,8004)RX,KK,GA,KR,XC
      READ (10,8004)TQV,IQ1,VHM,VRM,RGE2
      READ (10,8004)RGE3,VSP2,VSP3,THH,TRH
      READ (10,8004)RWT,TCY,THC,G,HCL
      READ (10,8004)KM,KMX,THCH,Q1,Q2
      READ (10,8004)Q3,EIN,KME(1),KME(2),KME(3)
      READ (10,8004)KME(4),KME(5),KME(6),CM(1),CM(2)
      READ (10,8004)CM(3),CM(4),CM(5),PBIS,PBVS
      READ (10,8004)TREP
      WRITE(5,8006)
8006  FORMAT(' FILE READ')
C*****INITIALIZE VALUES
C ORGANIZE TIMES FOR OPERATING CYCLE
      TT=0.
      TI1=THU+TCR
      TI2=TI1+TID
      TI3=TI2+TAC
C   BURNER INITIALIZATION
      N=NO
      NO2=N/2
      DO 200 I=1,N
      TOU(I)=T1
      TIN(I)=T1
      EY(I)=T1
200   EX(I)=T1
      TIN(N+1)=T1
      TA=T1
      TD=THMG-TWI
      FLAME=T1
      TOU(N+1)=T1
      CFL=1000.
      CFH=0.
      CFF=0
C   INITIALIZE CUMULATIVE HEAT INPUT AND METAL TEMPS
      DO 198 I=1,4
      TM(1,I)=T1
      TM(2,I)=T1
      TM(3,I)=T1
      TM(4,I)=T1
      TM(5,I)=(TWI+T1)/2.
      TM(6,I)=TWI
      M(I)=0.0
198   QHI(I)=0.
C  SET PRINTOUT OPTION
      J=Q2
C  INITIALIZE VEHICLE INERTIA
      VIN=0.0
C  INITIALIZE ENGINE AND VEHICLE SPEED
      OMEG=0.0
      SPV1=0.0
      SPVD=0.0
```

```
C   INITIALIZE WORKING TIME STEP
          DDT=DT
C   INITIALIZE TORQUES
          TQS=0.0
          TQV=0.0
          TNET=0.0
C   INITIALIZE ENGINE ANGLES
          EARAD=0.0
          REV=0.0
          NER=0
          NGC=-1
          MIR1=0.
          RGE=0.
C INITIALIZE ENGINE PRESSURE
          DO 950 I=1,4
950       P1(I)=PRL
C   INITIALIZE FLAG TO CALCULATE CONDITIONS AT CRANKING
          IG2=0
C   INITIALIZE OUTPUT FLAGS
          POF=0.0
          GDF=0.0
          GDI=TOTT/1024.
C******** DRAW GRAPHIC FRAME IF OPTION IS ON
C   GRAPHIC FRAME
          IF(Q1-1.00)158,157,158
C   DRAW OUTLINE
157       CALL CLEAR
          I1=0
          J1=0
          I2=1023
          J2=0
          CALL VECTOR(I1,J1,I2,J2)
          I1=1023
          J1=779
          CALL VECTOR(I2,J2,I1,J1)
          I2=0
          J2=779
          CALL VECTOR(I1,J1,I2,J2)
          I1=0
          J1=0
          CALL VECTOR(I2,J2,I1,J1)
          I1=700
          J1=0
          I2=700
          J2=779
          CALL VECTOR(I1,J1,I2,J2)
C   DIVIDE INTO 4 LAYERS LEFT SIDE
          I1=0
          J1=629
          I2=700
          J2=629
          CALL VECTOR(I1,J1,I2,J2)
          J1=479
          J2=479
          CALL VECTOR(I1,J1,I2,J2)
```

```
C DIVIDE INTO FOUR LAYERS, RIGHT SIDE
        I1=700
        J1=190
        I2=1023
        J2=190
        CALL VECTOR(I1,J1,I2,J2)
        J1=380
        J2=380
        CALL VECTOR(I1,J1,I2,J2)
        J1=570
        J2=570
        CALL VECTOR(I1,J1,I2,J2)
C DRAW SCHEDULED VEHICLE SPEED
        I1=0
        J1=632
        I2=TI2/TOTT*700
        J2=632
        CALL VECTOR(I1,J1,I2,J2)
        I1=TI3/TOTT*700
        J1=776
        CALL VECTOR(I2,J2,I1,J1)
        I2=700
        J2=776
        CALL VECTOR(I1,J1,I2,J2)
C DRAW SCHEDULED ENGINE SPEED
        I1=0
        J1=482
        I2=THU/TOTT*700
        J2=482
        CALL VECTOR(I1,J1,I2,J2)
        I1=THU/TOTT*700
        J1=554
        I2=TI2/TOTT*700
        J2=554
        CALL VECTOR(I1,J1,I2,J2)
C DRAW HOT METAL GOAL TICK (THMG)
        I1=0
        J1=200
        I2=10
        J2=200
        CALL VECTOR(I1,J1,I2,J2)
C DRAW COOLING WATER TEMP TICK (TWI)
        J1=10
        J2=10
        CALL VECTOR(I1,J1,I2,J2)
C CALCULATE DISPLAY PARAMETERS
        PDIF=PRH
        XLOW=VTD+VHDX+VCDA
        XDV=(ACY+BCY)*RC2
158     CONTINUE
```

```
C*****WRITE UNIFIED PRINTOUT--RETURN POINT FOR MAIN LOOP
401      IF(Q3-1.0)390,402,390
402      IF(TIM-POF)390,391,391
391      POF=POF+TREP
         WRITE(J,8025)TIM,CFF,REV,OMEG,SPV1,SPVD,DDT
8025     FORMAT(6F8.2,F8.5,2F8.2)
         WRITE(J,8022)TIN(1),TIN(2),TIN(3),TIN(4),TIN(5),TIN(6),TIN(7),
     1 TIN(8),TIN(9)
         WRITE(J,8022)EX(1),EX(2),EX(3),EX(4),EX(5),EX(6),EX(7),
     1 EX(8),FLAME
         WRITE(J,8022)TOU(1),TOU(2),TOU(3),TOU(4),TOU(5),TOU(6),TOU(7),
     1 TOU(8),TOU(9)
         DO 10 I=1,4
10       WRITE(J,8022)TM(1,I),TM(2,I),TM(3,I),TM(4,I),TM(5,I),P1(I),
     1 M(I),VT(1,I)
8022     FORMAT(9(F8.2))
         WRITE(J,8022)TNET,TQS,TQV,VIN,MIR1,RGE
C*****DISPLAY GRAPHIC DATA,PART 1
390      IF(Q1-1.)20,21,20
C CHECK TO SEE IF PLOTTING SHOULD BE DONE
21       IF(TIM-GDF)20,393,393
393      GDF=GDF+GDI
C SHOW FUEL FLOW RATE
         I1=TIM/TOTT*700
         J1=CFF/FFF*777
         CALL POINT(I1,J1)
C SHOW AVERAGE HEATER TEMP.
         J1=(TA-TWI)/TD*190+10
         CALL POINT(I1,J1)
C SHOW FLUE GAS TEMP. ENTERING PREHEATER
         J1=(TOU(N+1)-TWI)/TD*190+10
         CALL POINT(I1,J1)
C SHOW FLUE GAS TEMP. LEAVING PREHEATER
         J1=(TOU(1)-TWI)/TD*190+10
         CALL POINT(I1,J1)
C SHOW AVE. HOT METAL SPACE TEMP (NODE #1)
         X=0
         DO 145 I=1,4
145      X=TM(1,I)+X
         X=X/4.
         J1=(X-TWI)/TD*190+10
         CALL POINT(I1,J1)
C SHOW AVE METAL TEMP HOT END REGEN. (NODE #4)
         X=0
         DO 146 I=1,4
146      X=TM(4,I)+X
         X=X/4.
         J1=(X-TWI)/TD*190+10
         CALL POINT(I1,J1)
C SHOW AVE. METAL TEMP. MIDDLE REGEN. (NODE #5)
         X=0
         DO 147 I=1,4
147      X=TM(5,I)+X
         X=X/4.
         J1=(X-TWI)/TD*190+10
         CALL POINT(I1,J1)
         IF(TIM-THU)20,20,954
```

```
C SHOW ENGINE SPEED
954     J1=OMEG/OM1*72+482
        CALL POINT(I1,J1)
        IF(TIM-TI2)20,20,953
C SHOW VEHICLE SPEED
953     J1=SPV1/SPM*144+632
        CALL POINT(I1,J1)
20      CONTINUE
C*****DISPLAY GRAPHIC DATA, PART 2
C PLOTTING FOR EVERY TIME STEP OF 4 P-V DIAGRAMS
C CHECK TO SEE IF OPTION IS ON
        IF(Q1-1.)852,853,852
853     IF(TIM-THU)852,852,854
854     DO 985 I=1,4
        IPV(2,I)=(CVM(8,I)-XLOW)*323/XDV+700
        JPV(2,I)=P1(I)*190/PDIF+190*(4-I)
        CALL VECTOR(IPV(1,I),JPV(1,I),IPV(2,I),JPV(2,I))
        IPV(1,I)=IPV(2,I)
        JPV(1,I)=JPV(2,I)
985     CONTINUE
852     CONTINUE
C*****ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
C CHECK TO SEE IF HEAT UP TIME IS EXCEEDED
        IF(TIM-THU)503,502,502
503     IG1=0
        GOTO 501
C FIRST TIME CALCULATION OF GAS MASSES AND INITIALIZE PRESSURES
C   AND SET GAS TEMPS. TO CURRENT METAL NODE TEMPS.
502     IF(IG2-1)504,506,506
504     IG2=1
C REDUCE TIME STEP AT START OF CRANKING
        DDT=DDT/10.
        X=PRL*MW/R
        DO 507 I=1,4
C NODAL GAS MASSES
        W(1,1,I)=X*VHA(1,I)/TM(1,I)
        W(1,2,I)=X*VHM*2./(TM(1,I)+TM(2,I))
        W(1,3,I)=X*VHD*2./(TM(3,I)+TM(2,I))
        W(1,4,I)=X*VRM*2./(TM(4,I)+TM(3,I))
        W(1,5,I)=X*VRD/(TM(5,I)+TM(4,I))
        W(1,6,I)=X*VRD/(TM(6,I)+TM(5,I))
        W(1,7,I)=X*VCD/TWI
        W(1,8,I)=X*VCA(1,I)/TWI
C TOTAL GAS MASSES
        M(I)=0.
        DO 980 K=1,8
980     M(I)=M(I)+W(1,K,I)
C PRESSURES
        P1(I)=PRL
C INITIAL PRESSURE PLOT PARAMETERS
        JPV(1,I)=(P1(I)-PRL)*195/PDIF+195*(4-I)
C AVERAGE GAS AND METAL TEMPERATURES
        TGA(1,1,I)=TM(1,I)
        DO 981 K=2,6
        TMA(K,I)=(TM(K-1,I)+TM(K,I))/2.
981     TGA(1,K,I)=TMA(K,I)
        TMA(7,I)=TWI
        TMA(8,I)=TWI
        TGA(1,7,I)=TWI
        TGA(1,8,I)=TWI
```


C-2

```
C CUMULATIVE GAS VOLUMES
        CVG(1,I)=VHA(1,I)
        CVG(2,I)=CVG(1,I)+VHM
        CVG(3,I)=CVG(2,I)+VHD
        CVG(4,I)=CVG(3,I)+VRM
        CVG(5,I)=CVG(4,I)+VRD/2.
        CVG(6,I)=CVG(5,I)+VRD/2.
        CVG(7,I)=CVG(6,I)+VCD
        CVG(8,I)=VT(1,I)
C VOLUME PLOT PARAMETERS
        IPV(1,I)=(CVG(8,I)-XLOW)*323/XDV+700
507     CONTINUE
506     CONTINUE
C TEST TO SEE IF ENGINE SHOULD BE CRANKED
        IF(TIM-(THU+TCR))508,509,509
509     X=0.0
        GOTO 511
508     X=TST
511     TNET=TQS-TQV+X
C CALCULATE ANGLE INCREMENT
512     DANG=DDT**2*TNET/(EIN+VIN)+DDT*OMEG
C ADJUST TIME STEP SO THAT ANGLE INCR. IS >7 AND <30 DEG.
        IF(DANG-0.52360)515,515,513
513     DDT=DDT/2.
        GOTO 512
515     IF(DANG-0.12217)517,517,516
517     DDT=DDT*2.
        GOTO 512
C INDEX ENGINE ANGLE MEASURES
516     EARAD=DANG+EARAD
        EADEG=EARAD/RAD
        REV=REV+DANG/(2.*PI)
        IF(EADEG-360.)239,240,240
240     EADEG=EADEG-360.
        EARAD=EARAD-2.*PI
C ERRASE PV PLOT FIELD AFTER EVERY 5 REVOLUTIONS
        IF(Q1-1.)239,151,239
151     IF(NER-5)152,150,150
150     NER=0
        CALL ERASE
        GOTO 239
152     NER=NER+1
239     CONTINUE
C CHECK TO SEE IF ENGINE SHOULD BE IDLEING OR IN GEAR
        IF(TIM-TI2)519,519,520
C ADJUST ENGINE PRESSURES TO CONTROL SPEED WHILE ENGINE IS IDLEING
519     IG1=1
        IF(OMEG-OM1)830,840,840
840     IF(OMEG-(OM1+PBIS))841,841,842
842     MIR1=MIR
        GOTO 843
841     MIR1=MIR*(OMEG-OM1)/PBIS
843     X=PRL
        GOTO 855
830     IF(OMEG-(OM1-PBIS))831,831,832
831     MIR1=MIR
        GOTO 833
832     MIR1=MIR*(OM1-OMEG)/PBIS
833     X=PRH
855     CALL MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
```

```
C COMPUTE NEW ANGULAR VELOCITY
        OMEG=DANG/DDT
        GOTO 501
C ENGINE AND VEHICLE CONTROL WHILE ENGINE IS IN GEAR
520     IG1=2
C  GEAR CHANGE TIME APPLIED TO ALL GEARS
        IF(NGC)170,171,172
170     IF(TIM-(TI2+GCT))900,901,901
900     RGE=(TIM-TI2)*RGE1/GCT
        GOTO 910
901     IF(SPV1-VSP2)906,905,905
906     RGE=RGE1
        GOTO 910
905     NGC=0
        TIMX=TIM
        GOTO 910
171     IF(TIM-(TIMX+GCT))162,163,163
162     RGE=RGE1+(TIM-TIMX)*(RGE2-RGE1)/GCT
        GOTO 910
163     CONTINUE
        IF(SPV1-VSP3)907,908,908
907     RGE=RGE2
        GOTO 910
908     NGC=1
        TIMX=TIM
        GOTO 910
172     IF(TIM-(TIMX+GCT))166,167,167
166     RGE=RGE2+(RGE3-RGE2)*(TIM-TIMX)/GCT
        GOTO 910
167     RGE=RGE3
        GOTO910
C ADDITIONAL EFFECTIVE ENGINE INERTIA DUE TO VEHICLE ATTACHMENT
910     VIN=MIV*(RGE/(2.*PI))**2
C FIND SCHEDULED VEHICLE SPEED
        IF(TIM-TI3)912,911,911
912     SPVD=SPM*(TIM-TI2)/TAC
        GOTO 913
911     SPVD=SPM
C ADJUST ENGINE PRESSURE TO CONTROL VEHICLE SPEED
913     IF(SPV1-SPVD)930,940,940
940     IF(SPV1-(SPVD+PBVS))941,941,942
942     MIR1=MIR
        GOTO 943
941     MIR1=MIR*(SPV1-SPVD)/PBVS
943     X=PRL
        GOTO 955
930     IF(SPV1-(SPVD-PBVS))931,931,932
931     MIR1=MIR
        GOTO 933
932     MIR1=MIR*(SPVD-SPV1)/PBVS
933     X=PRH
955     CALL MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
C TORQUE DUE TO VEHICLE ROLLING FRICTION, AIR FRICTION
        RF=MIV*(0.151+0.000693*SPV1+0.0000195*SPV1**2)
        AF=KAR*SPV1**2
        TQV=(RF+AF)*RGE/(2.*PI)
C COMPUTE NEW ANGULAR VELOCITY
        OMEG=DANG/DDT
C COMPUTE NEW VEHICLE SPEED
        SPV1=OMEG*RGE/(2.*PI)
```

```
C ONE LINE CHECK DISPLAY TO SCREEN
501     WRITE(5,8030)TIM,CFF,REV,OMEG,SPV1,SPVD,RGE,NGC
8030    FORMAT(7E9.3,I3)
C INDEX TIME
        TIM=TIM+DDT
C*****END ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
C ***** BURNER AND HEAT CONDUCTION SUBPROGRAM
C INDEX APH METAL NODE TEMPERATURES
        DO 8050 I=1,N
8050    EX(I)=EY(I)
C FIND AVERAGE HEATER TEMPERATURE FOR CONTROL PURPOSES
400     TA=(TM(2,1)+TM(3,1)+TM(2,2)+TM(3,2)+TM(2,3)+TM(3,3)+TM(2,4)
     1+TM(3,4))/8.
C   TEMPERATURE ERROR (FOR CONTROL)
        TE=THMG-TA
C   CURRENT FUEL FLOW
        IF(TE)405,405,406
405     CFF=0.01*FFF
        GOTO409
406     IF(TE-TPB)408,407,407
407     CFF=FFF
        GOTO409
408     CFF=FFF*(TE)/TPB
409     CONTINUE
        FUEL=FUEL+CFF*DDT
C CHANGE HEAT TRANSFER FACTORS IF CFF HAS CHANGED SIGNIFICANTLY
        IF(CFF-CFL) 404,420,420
404     IF(CFF-CFH) 420,420,403
C   HEAT TRANSFER FACTOR, AIR SIDE
403     GAPH=CFF*RAF/AFAPH
        RE=DEQ*GAPH*2500
        CALL STANTN(RE,STN)
        X=UXX*STN*GAPH*1.19/CFF
        IF(X.GT.32.)X=32
        XY=EXP(X)
C   HEAT TRANSFER FACTOR, FLUE GAS SIDE
        GAPH=CFF*(RA1)/AFAPH
        RE=DEQ*GAPH*2500.
        CALL STANTN(RE,STN)
        X=STN*GAPH*1.19*UXY/CFF
        IF(X.GT.32.) X=32
        XZ=EXP(X)
C   HEAT TRANSFER FACTOR, GAS HEATER
        UH=(DOH*CFF*RA1/AMF/.0006)**0.592*0.00022/DOH
        X=4.*UH*AH/(CFF*CZ)
        IF(X.GT.32.) X=32.
        XH=EXP(X)
C  RESET FLOW BOUNDS
        CFH=1.2*CFF
        CFL=0.8*CFF
C CALCULATE APH AIR TEMPERAURES
420     DO 427 I=1,N
427     TIN(I+1)=EX(I)-(EX(I)-TIN(I))/XY
C  FIND FLAME TEMPERATURE
        FLAME=TIN(N+1)+DT2
```

```
C  DETERMINE OUTLET FLUE GAS TEMP.  FROM HEATERS
        DO 437 I=1,4
        X=(TM(2,I)+TM(3,I))/2.
  437   T3A(I)=X+(FLAME-X)/XH
C  AVERAGE FLUE GAS TEMPERATURES
        TOU(N+1)=(T3A(1)+T3A(2)+T3A(3)+T3A(4))/4.
C  EXIT FLUE GAS TEMPERATURES THROUGH AIR PREHEATER
        DO446 I=1,N
        K=N-I+1
  446   TOU(K)=EX(K)+(TOU(K+1)-EX(K))/XZ
C  CHANGE APH METAL NODE TEMP  DUE TO CONVECTION AND CONDUCTION
        DO 430 I=1,N
        X=CFF*RAF*CPA*(TIN(I+1)-TIN(I))*DDT
        Y=CFF*RA1*CPFG*(TOU(I+1)-TOU(I))*DDT
        IF(I-1)448,448,450
  450   IF(I-8)449,451,451
  448   ZZ=KAPH*(EX(I+1)-EX(I))*DDT
        GOTO 452
  449   ZZ=KAPH*(EX(I+1)-2.*EX(I)+EX(I-1))*DDT
        GOTO 452
  451   ZZ=-KAPH*(EX(I)-EX(I-1))*DDT
  452   CONTINUE
  430   EY(I)=EX(I)+(ZZ+Y-X)/CMAPH
C  CHANGE ENGINE METAL NODE TEMPS. DUE TO COND. AND OUTSIDE CONV.
        DO 489 I=1,4
        A=KME(1)*(TM(1,I)-TWI)*DDT
        B=KME(2)*(TM(2,I)-TM(1,I))*DDT
        TM1(1,I)=TM(1,I)+(B-A)/CM(1)
        A=KME(3)*(TM(2,I)-TM(3,I))*DDT
        C=(CFF/4.*RA1*CPFG*(FLAME-T3A(I))*DDT)/2.
        TM1(2,I)=TM(2,I)+(C-A-B)/CM(2)
        B=KME(4)*(TM(3,I)-TM(4,I))*DDT
        TM1(3,I)=TM(3,I)+(A+C-B)/CM(3)
        A=KME(5)*(TM(4,I)-TM(5,I))*DDT
        TM1(4,I)=TM(4,I)+(B-A)/CM(4)
        B=KME(6)*(TM(5,I)-TM(6,I))*DDT
  489   TM1(5,I)=TM(5,I)+(A-B)/CM(5)
C INDEX OF TM1(K,I) TO TM(K,I)
        DO 422 K=1,5
        DO 426 I=1,4
        TM(K,I)=TM1(K,I)
  426   CONTINUE
  422   CONTINUE
C AVERAGE METAL TEMPERATURES FOR ISOTHERMAL NODES
        DO 361 I=1,4
        DO 362 K=2,6
  362   TMA(K,I)=(TM(K,I)+TM(K-1,I))/2
        TMA(7,I)=TM(6,I)
  361   CONTINUE
C***** END OF BURNER AND HEAT CONDUCTION SUBPROGRAM
C*****CONTROL PROGRAM PART 2
C TEST FLAG TO DECIDE WHETHER TO GO ON TO NEXT SUBPROGRAM
        IF(IG1-1)401,425,425
```

```
C*****ENGINE TORQUE AND INTERNAL HEAT TRANSFER SUBPROGRAM
C  STEP 1--CALCULATE NEW ENGINE VOLUMES
425      X1=SQRT(XA-(RC*SIN(EARAD))**2)-RC*COS(EARAD)-XB
         X2=SQRT(XA-(RC*SIN(EARAD+PI2))**2)-RC*COS(EARAD+PI2)-XB
         X3=SQRT(XA-(RC*SIN(EARAD+PI))**2)-RC*COS(EARAD+PI)-XB
         X4=SQRT(XA-(RC*SIN(EARAD+PI32))**2)-RC*COS(EARAD+PI32)-XB
         VHA(2,1)=ACY*(RC2-X1)+VHDX
         VCA(2,1)=BCY*X2+VCDA
         VHA(2,2)=ACY*(RC2-X2)+VHDX
         VCA(2,2)=BCY*X3+VCDA
         VHA(2,3)=ACY*(RC2-X3)+VHDX
         VCA(2,3)=BCY*X4+VCDA
         VHA(2,4)=ACY*(RC2-X4)+VHDX
         VCA(2,4)=BCY*X1+VCDA
         DO 250 I=1,4
         VT(2,I)=VTD+VHA(2,I)+VCA(2,I)
250      CONTINUE
C CALCULATE NEW ENGINE SPACE CUMUMATIVE VOLUMES
         DO 982 I=1,4
         CVM(1,I)=VHA(2,I)
         CVM(2,I)=CVM(1,I)+VHM
         CVM(3,I)=CVM(2,I)+VHD
         CVM(4,I)=CVM(3,I)+VRM
         CVM(5,I)=CVM(4,I)+VRD/2.
         CVM(6,I)=CVM(5,I)+VRD/2.
         CVM(7,I)=CVM(6,I)+VCD
         CVM(8,I)=VT(2,I)
982      CONTINUE
C STEP 2--CHANGE IN GAS VOLUMES, TEMPERATURES AND GAS NODE INVENTORIES
C     OF WORKING SPACE THAT CAN HAVE ITS GAS INVENTORY ADJUSTED. X=
C VOLUME OF GAS ADDED(+) OR REMOVED(-) AT CURRENT PRESSURE AND TEMP.
C     FOR THAT WORKING SPACE
         Y=(P1(IG3)/PX)**KR
         X=VT(1,IG3)*(1.-Y)
C GAS INVENTORY CHANGE
         IF(X)102,101,101
C TEMP. OF ADDED GAS
101      YY=TWI*(PX/P1(IG3))**GA
C MASS ADDED
         M2=PX*X/(YY*XC)
C NEW TEMPERATURES DUE TO INVENTORY CHANGE
102      ZZ=(PX/P1(IG3))**GA
         DO 807 K=1,8
807      TGA(1,K,IG3)=TGA(1,K,IG3)*ZZ
C ADJUSTMENT OF COLD SPACE TEMP. WITH GAS ADDITION
         IF(X.GT.0)TGA(1,8,IG3)=(TGA(1,8,IG3)*W(1,8,IG3)+YY*M2)/
     1   (W(1,8,IG3)+M2)
C NEW PRESSURE DUE TO INVENTORY CHANGE
         P1(IG3)=PX
C NEW CUM. VOL. AND GAS NODE INVENTORIES DUE TO GAS ADDED OR REMOVED
         IF(X)800,801,801
C GAS ADDED OR NO CHANGE
801      DO 802 K=1,7
802      CVG(K,IG3)=CVG(K,IG3)*Y
         W(1,8,IG3)=W(1,8,IG3)+M2
         GOTO 803
```

```
C GAS REMOVED
 900    ZZ=1.
        DO 804 K=1,8
        CVG(K,IG3)=CVG(K,IG3)*Y
        IF(CVG(K,IG3)-CVM(8,IG3))804,804,806
 806    IF(ZZ)103,103,104
 104    W(1,K,IG3)=W(1,K,IG3)*(CVM(8,IG3)-CVG(K-1,IG3))/
     1  (CVG(K,IG3)-CVG(K-1,IG3))
        ZZ=0.
        GOTO 105
 103    W(1,K,IG3)=0.
 105    CVG(K,IG3)=CVM(8,IG3)
 804    CONTINUE
C RE-ADD MASSES
 803    M(IG3)=0.
        DO 118 K=1,8
 118    M(IG3)=M(IG3)+W(1,K,IG3)
C STEP 3-DETERMINE PRESSURE, TEMPERATURE AND VOLUME CHANGES OF ORIGINAL
C    VOLUMES DUE TO TOTAL VOLUME CHANGE ASSUMING NO HEAT TRANSFER
        DO290 I=1,4
C TOTAL VOLUME RATIO
        XX(I)=CVG(8,I)/CVM(8,I)
C  NEW GAS TEMPERATURES
        XT(I)=XX(I)**(KK-1)
        DO 951 K=1,8
 951    TGA(1,K,I)=TGA(1,K,I)*XT(I)
C  CUMULATIVE VOLUMES OF GAS NODES AFTER TOTAL VOLUME CHANGE
        DO 983 K=1,8
 983    CVG(K,I)=CVG(K,I)/XX(I)
 290    CONTINUE
C STEP 4--COMPUTATION OF TEMPERATURE AND MASS NOW IN EACH
C    ENGINE SPACE DUE TO GAS FLOW BUT NO HEAT TRANSFER
C    THIS VERSION ALLOWS UNLIMITED MASS FLOW DURING ONE TIME STEP
C CALCULATE FOR THE 4 WORKING SPACES
        DO 380 I=1,4
C LET K=SOLID INDEX AND L=GAS INDEX
        K=1
        L=1
C ZERO OUT MASS ARRAY AFTER MASS FLOW
        DO 349 II=1,8
        TGA(2,II,I)=0
 349    W(2,II,I)=0.
C SET SECOND TIME FLAG
        II=1
C RETURN POINT OF DECISION TREE
 348    IF(CVG(L,I)-CVM(K,I))345,346,347
C**** CUM. GAS VOL. LESS THAN CUM. METAL VOLUME
 345    IF(II)354,354,355
 354    II=1
        W(2,K,I)=RM
        TGA(2,K,I)=TGA(1,L,I)
        GOTO358
 355    Y=W(2,K,I)
        W(2,K,I)=W(2,K,I)+W(1,L,I)
        TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*W(1,L,I))/W(2,K,I)
 358    CONTINUE
```

```
C INDEX GAS NODE FLAG AND RETURN
        L=L+1
C CHECK FOR END OF MASS FLOW CALCULATION
        IF(L.GE.9) GOTO 310
C RETURN
        GOTO 348
C**** CUM. GAS VOL. EXACTLY EQUAL TO CUM. METAL VOLUME.
C CHECK FIRST TIME FLAG
346     IF(II)810,810,850
C ADDITION OF METAL NODE LEADS TO EQUAL VOLUMES
810     W(2,K,I)=RM
        TGA(2,K,I)=TGA(1,L,I)
        GOTO 851
C ADDITION OF GAS NODE LEADS TO EQUAL VOLUMES
C FIND MASS TO COMPLETE METAL NODE SPACE
850     Y=W(2,K,I)
        W(2,K,I)=W(2,K,I)+W(1,L,I)
C FIND AVERAGE TEMP. OF GAS NOW IN METAL NODE SPACE
        TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*W(1,L,I))/W(2,K,I)
C SET FIRST FLAG
851     II=1
C INDEX SOLID AND GAS NODE FLAGS
        L=L+1
        K=K+1
C CHECK FOR END OF MASS FLOW CALCULATION
        IF(K.GE.9.OR.L.GE.9) GOTO 310
C RETURN
        GOTO 348
C**** CUM. GAS VOL. GREATER THAN CUM. METAL VOLUME.
347     IF(K.EQ.1.AND.L.EQ.1) GOTO 350
        GOTO 351
C FIRST NODE FOR GAS AND METAL
350     W(2,K,I)=W(1,L,I)*CVM(K,I)/CVG(L,I)
        TGA(2,K,I)=TGA(1,L,I)
        RM=W(1,L,I)-W(2,K,I)
        GOTO 353
C GENERAL CASE
C CHECK FIRST TIME FLAG
351     IF(II)343,343,344
C FIRST TIME FOR NEW GAS NODE
344     RR=(CVM(K,I)-CVG(L-1,I))/(CVG(L,I)-CVG(L-1,I))
        RM=(1.-RR)*W(1,L,I)
        X=RR*W(1,L,I)
        Y=W(2,K,I)
        W(2,K,I)=W(2,K,I)+X
        TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*X)/W(2,K,I)
        GOTO 353
C AFTER THE FIRST TIME
343     RR=(CVM(K,I)-CVM(K-1,I))/(CVG(L,I)-CVM(K-1,I))
        W(2,K,I)=RM*RR
        RM=RM-W(2,K,I)
        TGA(2,K,I)=TGA(1,L,I)
C RESET FIRST FLAG ON GAS VOLUME SHORT SIDE
353     II=0
C INDEX SOLID NODE FLAG
        K=K+1
C CHECK FOR END OF FLOW CALCULATION
        IF(K.GE.9) GOTO 310
```

```
C RETURN
             GOTO 348
C FIND AND SHOW TOTAL MASS AFTER MASS FLOW
310          X=0.
             DO 326 K=1,8
326          X=X+W(2,K,I)
             ERRFL=M(I)-X
             IF(ABS(ERRFL)-.1)379,379,329
329          WRITE(J,330)ERRFL,I
330          FORMAT(' FLOW ERROR IS',E10.4,' IN WORKING SPACE #',I2)
             DO 153 K=1,8
153          WRITE(J,154)K,W(1,K,I),W(2,K,I),CVM(K,I),CVG(K,I),
         1   TGA(1,K,I),TGA(2,K,I)
154          FORMAT(I3,6F10.4)
             STOP
379          CONTINUE
380          CONTINUE
C STEP 5--CHANGE IN TEMPERATURE OF GAS AND METAL NODES DUE TO
C       HEAT TRANSFER WITH NO VOLUME CHANGE
C  IN GAS COOLER
             DO 690 I=1,4
C HEAT RECEIVED BY METAL NODE 1
             QM(1)=CV*W(2,2,I)*(TGA(2,2,I)-TMA(2,I))/2.
C HEAT RECEIVED BY METAL NODE 2
             X=CV*W(2,3,I)*(TGA(2,3,I)-TMA(3,I))/2.
             QM(2)=QM(1)+X
C HEAT RECEIVED BY METAL NODE 3
             Y=CV*W(2,4,I)*(TGA(2,4,I)-TMA(4,I))/2.
             QM(3)=X+Y
C HEAT RECEIVED BY METAL NODE 4
             X=CV*W(2,5,I)*(TGA(2,5,I)-TMA(5,I))/2.
             QM(4)=Y+X
C HEAT RECEIVED BY METAL NODE 5
             Y=CV*W(2,6,I)*(TGA(2,6,I)-TMA(6,I))/2.
             QM(5)=X+Y
C HEAT RECEIVED BY METAL NODE 6
             X=CV*W(2,7,I)*(TGA(2,7,I)-TMA(7,I))/2.
             QM(6)=Y+X
C HEAT RECEIVED BY METAL NODE 7
             QM(7)=X
C CHANGE IN AVERAGE GAS TEMPERATURES DUE TO HEAT TRANSFER
             DO 363 K=2,7
363          TGA(2,K,I)=TMA(K,I)
C CHANGE IN METAL NODE TEMPERATURES DUE TO HEAT TRANSFER
             DO 382 K=1,5
             TM(K,I)=TM(K,I)+QM(K)/CM(K)
382          CONTINUE
690          CONTINUE
C STEP 6--NEW PRESSURES FOR EACH SPACE DUE TO HEAT TRANSFER WITH NO
C            VOLUME CHANGE
             DO 740 I=1,4
C    HOT SPACE
             P3(I,1)=W(2,1,I)*XC*TGA(2,1,I)/VHA(2,I)
C    HEATER MANIFOLD
             P3(I,2)=W(2,2,I)*XC*TGA(2,2,I)/VHM
C    HEATER
             P3(I,3)=W(2,3,I)*XC*TGA(2,3,I)/VHD
```

```
C    REGENERATOR MANIFOLD
          P3(I,4)=W(2,4,I)*XC*TGA(2,4,I)/VRM
C    REGENERATOR HOT HALF
          P3(I,5)=W(2,5,I)*XC*TGA(2,5,I)/(VRD/2.)
C    REGENERATOR COLD HALF
          P3(I,6)=W(2,6,I)*XC*TGA(2,6,I)/(VRD/2.)
C    COOLER
          P3(I,7)=W(2,7,I)*XC*TGA(2,7,I)/VCD
C    COLD SPACE
          P3(I,8)=W(2,8,I)*XC*TGA(2,8,I)/VCA(2,I)
C STEP 7--ADIABATIC PRESSURE EQUILIBRATION AT CONSTANT TOTAL VOLUME
C    FINAL COMMON PRESSURE FOR INCREMENT
          X=VHA(2,I)*P3(I,1)**KR
          X=X+VHM*P3(I,2)**KR
          X=X+VHD*P3(I,3)**KR
          X=X+VRM*P3(I,4)**KR
          X=X+VRD/2.*P3(I,5)**KR
          X=X+VRD/2.*P3(I,6)**KR
          X=X+VCD*P3(I,7)**KR
          X=X+VCA(2,I)*P3(I,8)**KR
          P4(I)=(X/VT(2,I))**KK
C STEP 7A-- GAS NODE TEMPERATURES AFTER ADIABATIC PRESSURE
C              EQUILIBRATION
          DO 133 K=1,8
133       TGA(2,K,I)=TGA(2,K,I)*(P4(I)/P3(I,K))**GA
C STEP 7B-- CUMULATIVE VOLUMES OF GAS NODES DUE TO PRESSURE
C              EQUILIBRATION
          CVG(1,I)=W(2,1,I)*XC*TGA(2,1,I)/P4(I)
          DO 134 K=2,8
134       CVG(K,I)=CVG(K-1,I)+W(2,K,I)*XC*TGA(2,K,I)/P4(I)
C CORRECT SMALL ERROR IN VOLUME
          CVG(8,I)=VT(2,I)
C STEP 8-- INITIALIZE QUANTITIES FOR NEXT INCREMENT
C    TEMPERATURE
          DO 364 K=1,8
364       TGA(1,K,I)=TGA(2,K,I)
C    VOLUMES
          VT(1,I)=VT(2,I)
          VCA(1,I)=VCA(2,I)
          VHA(1,I)=VHA(2,I)
C    PRESSURES
          P1(I)=P4(I)
C    MASSES
          DO 750 K=1,8
750       W(1,K,I)=W(2,K,I)
740       CONTINUE
C STEP 9--DETERMINE ENGINE TORQUE AT OUTPUT SHAFT
C   INDICATED ENGINE TORQUE, FORCE ON PISTONS, NEWTONS
          FP(1)=100.*(-P1(1)*ACY+P1(4)*BCY-(P1(4)-0.1)*CCY)
          FP(2)=100.*(P1(1)*BCY-P1(2)*ACY-(P1(1)-0.1)*CCY)
          FP(3)=100.*(P1(2)*BCY-P1(3)*ACY-(P1(2)-0.1)*CCY)
          FP(4)=100.*(P1(3)*BCY-P1(4)*ACY-(P1(3)-0.1)*CCY)
C   TORQUE ON EACH CRANK, N-M, CCW IS POSITIVE
          TQ(1)=RC/100.*SIN(EARAD)*FP(1)
          TQ(2)=RC/100.*SIN(EARAD+PI2)*FP(2)
          TQ(3)=RC/100.*SIN(EARAD+PI)*FP(3)
          TQ(4)=RC/100.*SIN(EARAD+PI32)*FP(4)
```

```
C   INDICATED TORQUE FOR ENGINE
          TQI=TQ(1)+TQ(2)+TQ(3)+TQ(4)
          PAV=(P1(1)+P1(2)+P1(3)+P1(4))/4.
C   SHAFT TORQUE FOR ENGINE
          SP=OMEG/(2.*PI)
          TQS=TQI*ME/100.*(.99862-.0000145*OMEG**2)*(1.-OMEG*.000491*
        1 PAV**(-1.841))
C*****END OF ENGINE TORQUE AND INTERNAL H.T. SUBPROGRAM
C*****CONTROL PROGRAM PART 3
790       IF(TIM-TOTT)401,795,795
C*****FINAL SUMMARY REPORT
795       WRITE(J,798)FUEL,TOTT,SPV1
798       FORMAT(' FUEL,TOTT,SPV1',3F10.3)
5000      STOP
          END
          SUBROUTINE MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
          DIMENSION P1(4)
          REAL M2,MIR1
          IF(EADEG-45.)860,860,890
890       IF(EADEG-135.)862,862,856
856       IF(EADEG-225.)864,864,857
857       IF(EADEG-315.)858,858,860
C GAS CHANGE IN WORKING SPACE 1
858       IG3=1
          PX=X+(P1(1)-X)*EXP(-MIR1*DDT)
          GOTO875
C GAS CHANGE IN WORKING SPACE 4
860       IG3=4
          PX=X+(P1(4)-X)*EXP(-MIR1*DDT)
          GOTO875
C GAS CHANGE IN WORKING SPACE 3
862       IG3=3
          PX=X+(P1(3)-X)*EXP(-MIR1*DDT)
          GOTO875
C GAS CHANGE IN WORKING SPACE 2
864       IG3=2
          PX=X+(P1(2)-X)*EXP(-MIR1*DDT)
875       RETURN
          END
          SUBROUTINE STANTN(RE,STN)
          IF(RE-2000)100,100,200
100       STN=EXP(1.6908-0.9363*ALOG(RE))
          GOTO300
200       STN=EXP(-4.0555-0.1803*ALOG(RE))
300       RETURN
          END
```

```
C SUBROUTINE USED TO ERASE PV DISPLAY FIELD
        SUBROUTINE ERASE
        INTEGER*1 GS,US,CA,ES,DE,AA,YH,YL,XH,XL
        DATA GS,US,CA,ES,DE,AA/29,31,24,27,127,97/
        DO 30 JP=710,1013
        CALL CONOUT(GS)
        CALL CONOUT(ES)
        CALL CONOUT(DE)
        YH=777/32+32
        YL=MOD(777,32)+96
        XH=JP/32+32
        XL=MOD(JP,32)+64
        CALL CONOUT(YH)
        CALL CONOUT(YL)
        CALL CONOUT(XH)
        CALL CONOUT(XL)
        DO 10 I=1,200
        M=I+1
 10     CONTINUE
        YH=2/32+32
        YL=MOD(2,32)+96
        CALL CONOUT(YH)
        CALL CONOUT(YL)
        CALL CONOUT(XH)
        CALL CONOUT(XL)
        DO 20 I=1,200
        M=I+1
 20     CONTINUE
        CALL CONOUT(ES)
        CALL CONOUT(AA)
        CALL CONOUT(US)
        CALL CONOUT(CA)
 30     CONTINUE
        RETURN
        END
```

6.0 PROGRAM USERS MANUAL

This section gives the directions for using the program described in this report. It is sometimes particular to the Altos computer used in the program development but the intent of each instruction is given so that another computer can also be used. Instructions are as follows:

6.1 Load Program CNTLA

A. Turn on computer.
B. Insert disc.
C. Type CNTLA (return)
D. Following message appears on screen

```
DATA READ IN
TYPE 1 LEAVE IN BASE CASE
TYPE 2 BRING IN STORED DATA FROM LAST CASE
```

When the program starts, the data statements are always read. This initiates the base case. The program has been used before. A file has been created which transfers the input values to program CNTLB. If the operator has already made a lot of changes and wants to make some more, he should type 2 and then key (return). If he is starting or wants to start over with the base case, he should type 1 and (return).

E. Type either 1 or 2 and (return).
F. The following directions appear on the screen:

```
CNTLA INPUT ADJUSTMENT PROGRAM. TO CHANGE TYPE 2 DIGIT INPUT
NUMBER, A SPACE, AND THE NEW INPUT VALUE WITH A DECIMAL POINT.
TO CONTINUE HIT RETURN.
```

G. Hit return.

H. A table appears on the screen as shown in Table 6.1. To save space the input parameters are identified by numbers only and the values are given just by a number. Table 6.2 gives the identity of each input parameter. This table is given in numerical order of the input numbers. The symbol used in the program, the meaning, the resident value and the units are given.

Table 6.3 gives the same information organized by subject. If one wants to change a particular operating condition, it would be easier to look up the variable number in Table 6.3. Table 6.2 would be useful if the question is what a particular variable number means or if additional variables are needed to be added.

I. To change a variable type the variable number, a space and then the new variable value with a decimal point in the appropriate place. After pressing (return), the change menue is redisplayed with the new change.

This process may be repeated as many times as desired. When calculation is to proceed, type 99 and (return). The word STOP will show on the screen when the program is finished and the intermediate values have been filed in FORT10.DAT. Also the prompt >A will appear. The operator is now finished with CNTLA. In fact, he is out of it.

Table 6.1

INPUT PARAMETER TABLE FOR BASE CASE

OPERATING CONDITIONS BY NUMBER

01	922.200	02	50.000	03	300.000	04	1575.000	05	40.000
06	300.000	07	.500	08	90.000	09	1	10	.540
11	36.000	12	.472	13	4.850	14	20.000	15	7.950
16	1.000	17	1.000	18	30.000	19	90.000	20	22.400
21	2.325	22	13.650	23	10.160	24	4.060	25	.472
26	.084	27	36.000	28	11.590	29	6.000	30	3.500
31	2.500	32	.200	33	0.000	34	0.000	35	0.000
36	196.020	37	.950	38	.115	39	12.900	40	312.000
41	1100.000	42	36.000	43	.472	44	1.120	45	7.950
46	.640	47	25.580	48	.010	49	10.000	50	5.000
51	.700	52	50.000	53	.500	54	10.000	55	.084
56	1000.000	57	150.000	58	16.550	59	8.000	60	46.432
61	1.000	62	1.000	63	2.000	64	4.470	65	13.420
66	1.500	67	.500	68	.410	69	1.270	70	.381
71	.041	72	10.030	73	.200	74	.017	75	.381
76	1.000	77	2.000	76	1.000	79	50.000	80	5.000
81	1.000	82	5.000	83					

II XXXXXXXXXX TYPE 99 TO CALCULATE' AND FILE INTERMEDIATE VALUES

Table 6.2

CNTLA CHANGE TABLE BY NUMBER

Number	Symbol	Meaning	Resident Value	Units
1	THMG	Temperature, hot metal, goal	922.2	K
2	TPB	Temperature, proportional band in hot metal	50.	K
3	TWI	Temperature, water, inlet	300.	K
4	FWI	Flow of cooling water for entire engine	1575.	g/sec
5	OM1	Desired idle speed of engine	40.	rad/sec
6	T1	Ambient air temperature	300.	K
7	DT	Initial time step	0.5	sec
8	ME	Mechanical efficiency, engine	90.	%
9	Z	Flag for working fluid: 1 for H_2, 2 for He, 3 for air	1	--
10	RGE1	Vehicle travel per engine revolution in first gear	0.54	meters
11	NTHM	Number of tubes in heater manifold	36	--
12	DIHM	Inside diameter of tubes in heater manifold	0.472	cm
13	FFF	Full fuel flow	4.85	g/sec
14	THU	Time for engine warm-up, before cranking	20	sec
15	LHM	Length of tubes in heater manifold	7.95	cm
16	TCR	Duration of starting motor torque	1.0	sec
17	TID	Idle time after cranking	1.0	sec
18	TAC	Vehicle acceleration time	30	sec
19	TOTT	Total simulation time	90	sec
20	SPM	Cruising speed of vehicle	22.4	m/sec
21	RC	Radius of engine crank	2.325	cm
22	LCR	Length of connecting rod	13.65	cm
23	DCY	Diameter of cylinder	10.16	cm
24	DDR	Diameter of drive rod (at seal)	4.06	cm
25	DIH	Inside diameter of heater tubes	0.472	cm
26	WTHM	Wall thickness of tubes in heater manifold	0.084	cm
27	NTH	Number of heater tubes per cylinder	36	--
28	VHDX	Extra hot dead volume in end clearance and hot cap clearance per cylinder	11.59	cm^3
29	NR	Number of regenerators per cylinder	6	--

Table 6.2 (continued)

Number	Symbol	Meaning	Resident Value	Units
30	DR	Diameter of each regenerator	3.5	cm
31	LR	Length of regenerator	2.5	cm
32	FF	Fraction of regenerator volume filled with solid (if zero program calculates FF from dimensions below)	0.2	--
33	NS	Number of screens per regenerator	0.0	--
34	MSH	Mesh size	0.0	wires/cm
35	THW	Thickness of wire in screens of regenerator	0.0	cm
36	VCDX	Cold dead volume not in gas cooler or cold space	196.02	cm^3
37	FCA	Fraction of VCDX that is adiabatic	0.95	--
38	DIC	Diameter of inside of cooler tubes	0.115	cm
39	LC	Length of cooler tubes	12.9	cm
40	NTC	Number of cooler tubes per cylinder	312	--
41	MIV	Mass, inertia of vehicle	1100	Kg
42	NTRM	Number of tubes in regenerator manifold	36	--
43	DIRM	Inside diameter of tubes in regenerator manifold	0.472	cm
44	AFR	Frontal area of vehicle times shape coefficient	1.12	m^2
45	LRM	Length of tubes in regenerator manifold	7.95	cm
46	DOH	Outside diameter of heater tubes	0.640	cm
47	LHH	Heated length of heater tubes	25.58	cm
48	TMAPH	Thickness of metal separating each flow passage in air preheater	0.01	cm
49	LAPH	Length of air preheater	10.0	cm
50	WAPH	Width of each air preheater passage	5.0	cm
51	TAPH	Thickness of each air preheater flow passage	0.3	cm
52	NAPH	Number of air preheater flow passages in each direction	50	--
53	PRL	Pressure of working gas in low pressure reservoir	0.5	MPa
54	PRH	Pressure of working gas in high pressure reservoir	10.0	MPa
55	WTRM	Wall thickness of tubes in regenerator manifold	0.084	cm

Table 6.2 (continued)

Number	Symbol	Meaning	Resident Value	Units
56	TST	Starting motor torque	1000.	Newton-meters
57	MIR	Maximum time constant for changing working gas pressure	150.	sec^{-1}
58	RAF	Mass ratio of air to fuel	16.55	g/g
59	NO	Number of nodes in air preheater	8	--
60	LHV	Lower heating value of fuel	46.432	Kj/g
61	GCT	Gear change time	1.0	sec
62	RGE2	Vehicle travel per engine revolution in second gear	1.0	meters
63	RGE3	Vehicle travel per engine revolution in third gear	2.0	meters
64	VSP2	Vehicle speed to change to second gear	4.47	m/sec
65	VSP3	Vehicle speed to change to third gear	13.42	m/sec
66	THH	Thickness of hot cylinder head	1.5	cm
67	TRH	Thickness of regenerator head	0.5	cm
68	RWT	Average regenerator wall thickness (for heat conduction)	0.41	cm
69	TCY	Average engine cylinder wall thickness (for heat conduction)	1.27	cm
70	THC	Thickness of hot cap cylinder	0.381	cm
71	G	Gap between hot cap and cylinder wall	0.0406	cm
72	HCL	Hot cap length	10.03	cm
73	KM	Thermal conductivity of engine walls	0.2	w/cm K
74	KMX	Thermal conductivity of regenerator matrix	0.017	w/cm K
75	THCH	Thickness of hot cap head	0.381	cm
76	Q1	Graphic option, 1 for yes	1.0	--
77	Q2	Printout option, 5 to console, 2 to printer	2.0	--
78	Q3	Periodic report printout option, 1 for yes	1.0	--
79	EIN	Engine inertia	50	Kg m^2
80	PBIS	Proportional band on engine idle speed	5.0	rad/sec
81	PBVS	Proportional band on vehicle speed	1.0	m/sec
82	TREP	Time interval for periodic report printout	5.0	sec

Table 6.3

CNTLA CHANGE TABLE ORGANIZED BY SUBJECT

Subject	No.	Symbol	Resident Value	Units
Solution output control				
Graphics flag (1 for yes)	76	Q1	1.0	--
Output flag (2 for printer, 5 for screen)	77	Q2	2.0	--
Periodic report flag (1 for yes)	78	Q3	1.0	--
Time interval between printouts	82	TREP	5.0	sec
Initial time step	7	DT	0.5	sec
Nodes in air preheater	59	NO	8	--
Driving Cycle				
Warm-up time	14	THU	20.	sec
Cranking time	16	TCR	1.0	sec
Cranking torque	56	TST	1000.	N-m
Idling time	17	TID	1.0	sec
Desired idle speed	5	OM1	40.	rad/sec
Proportional band on idle speed	80	PBIS	5.0	rad/sec
Acceleration time	18	TAC	30.	sec
Cruising speed	20	SPM	22.4	m/sec
Total simulation time	19	TOTT	90.	sec
Proportional band on vehicle speed	81	PBVS	1.0	m/sec
Gear ratio, vehicle travel/revolution				
first gear	10	RGE1	0.54	m
second gear	62	RGE2	1.0	m
third gear	63	RGE3	2.0	m
Gear change speeds				
to second gear	64	VSP2	4.47	m/sec
to third gear	65	VSP3	13.42	m/sec
Time to change gears	61	GCT	1.0	sec
Maximum time constant for changing working gas pressure	57	MIR	150	sec^{-1}
Engine Operating Conditions				
Temperatures				
goal for heater tubes	1	THMG	922.2	K
proportional band on heater tubes	2	TPB	50.	K
water inlet	3	TWI	300	K
ambient air	6	T1	300	K

Table 6.3 (continued)

Subject	No.	Symbol	Resident Value	Units
Engine Operating Conditions (continued)				
Pressures				
low reservoir	53	PRL	0.5	MPa
high reservoir	54	PRH	10.0	MPa
Working fluid (1 for H_2, 2 for He, 3 for air)	9	Z	1	--
Flows				
maximum fuel	13	FFF	485	g/sec
cooling water	4	FWI	1575	g/sec
Lower Heating Volume of Fuel	60	LHV	46.432	K j/g
Ratio of air to fuel	58	RAF	16.55	g/g
Engine Dimensions				
Vehicle				
inertial mass	41	MIV	1100	Kg
frontal area times space coefficient	44	AFR	1.12	m^2
Air preheater				
plate thickness	48	TMAPH	0.01	cm
length	49	LAPH	10.	cm
width of each passage	50	WAPH	5	cm
thickness of each passage	51	TAPH	0.3	cm
number of air passages each way	52	NAPH	50	--
Hot and cold spaces				
Diameter of engine cylinder	23	DCY	10.16	cm
thickness of engine cylinder wall	69	TCY	1.27	cm
end clearance and hot cap clearance volume	28	VHDX	11.59	cm^3
thickness of head	66	THH	1.5	cm
gap between hot cap and cylinder wall	71	G	0.0406	cm
length of hot cap	72	HCL	10.03	cm
thickness of hot cap cylinder	70	THC	0.381	cm
thickness of hot cap head	75	THCH	0.381	cm
thermal conductivity of engine metal	73	KM	0.2	w/cm K
diameter of piston drive rod	24	DDR	4.06	cm
Heater manifold				
number of tubes per cylinder	11	NTHM	36	--
inside diameter	12	DIHM	0.472	cm
length	15	LHM	7.95	cm
wall thickness	26	WTHM	0.084	cm

Table 6.3 (continued)

Subject	No.	Symbol	Resident Value	Units
Engine Dimensions (continued)				
Heater				
ID of tubes	25	DIH	0.472	cm
tubes per cylinder	27	NTH	36	--
outside diameter	46	DOH	0.640	cm
heated length	47	LHH	25.58	cm
Regenerator manifold				
number of tubes per cylinder	42	NTRM	36	--
ID	43	DIRM	0.472	cm
length	45	LRM	7.95	cm
wall thickness	55	WTRM	0.084	cm
Regenerator				
thermal conductivity of matrix	74	KMX	0.017	w/cm K
number per cylinder	29	NR	6	--
diameter	30	DR	3.5	cm
length	31	LR	2.5	cm
wall thickness	68	RWT	0.41	cm
fraction of matrix filled with solid	32	FF	0.2	--
number of screens per regenerator	33	NS	0.	--
mesh size	34	MSH	0.0	wires/cm
thickness of wire in regenerator	35	THW	0.0	cm
thickness of regenerator head	67	TRH	0.5	cm
Cooler				
number of tubes per cylinder	40	NTC	312.	--
length of tubes	39	LC	12.9	cm
ID of tubes	38	DIC	0.115	cm
Cooler manifold				
dead volume	36	VCDX	196.02	cm^3
fraction adiabatic	37	FCA	0.95	--
Drive				
cylinders per engine	--	---	4	--
radius of crank	21	RC	2.325	cm
length of connecting rod	22	LCR	13.65	cm
engine inertia	79	EIN	50	Kg m^2
mechanical efficiency	8	ME	90	%

Besides being able to change any input variable involving engine dimensions and operating conditions, there are some computer solution options that should be discussed here.

Number 76 - Graphic Flag. If #76 is 1.0, then CNTLB will go into the graphic parts of the program. If #76 is 0.0, it will not. If the computer does not have graphic capability or the operator does not want to use it, #76 should be 0.0.

Number 77 - Output Flag. If #77 is 2.0, then CNTLB will direct its periodic and final output to the printer. If #77 is 5.0, it will be directed to the screen on the console. If #77 is 2.0, be sure the printer is on or the solution will stop with no indication of why.

Number 78 - Periodic Report Flag. If #78 is 1.0, a periodic report is printed out or displayed. If in CNTLB #78 is 0.0, then CNTLB will not produce periodic reports.

Number 82 - Repetition Rate for Periodic Reports. #82 gives the desired number of seconds between periodic reports. After this desired time is exceeded, the next periodic report will be given. This number is useful in controlling the amount of output from CNTLB to give an adequate but not overwhelming amount.

Number 7 - Initial Time Step. #7 gives the time step used in the heat up section of the solution at the start of CNTLB. The program WARM (Appendix A) was used to show that 8 nodes and a time increment of 0.5 second gives adequate accuracy for the solution. #7 can be changed for other time steps. When the engine starts rotating, the program automatically adjusts the time step.

Number 59 - Nodes in Air Preheater. Presently the number of nodes in the air preheater is fixed at 8. It cannot be changed in CNTLA. It can in WARM (see Appendix A).

CNTLA produces a data file called FORT10.DAT which is read by CNTLB. The information is transferred by the position in this data file. Therefore, the write statements in CNTLA and the read statements in CNTLB must be identical. Table 6.4 shows the file for the base case.

6.2 Load Program CNTLB

A. Type CNTLB (RETURN).

B. Be certain printer is on. (Base case has the intermediate printout go to the printer every 5 seconds of real time.)

C. The message FILE READ appears on the screen. This shows that the data file prepared by CNTLA has been read in.

The solution then proceeds as required by the contract without any operator attention. Pressing the CNTL key and S at the same time will stop the solution or start it again.

Table 6.4

DATA TRANSFER FILE FOR BASE CASE
(Called FORT10.DAT)

(See listing of either CNTLA or CNTLB for identity of numbers)

922.200	50.000	300.000	1575.000	40.000
300.000	.500	90.000	.540	.800
36.000	.472	.850	20.000	7.950
1.000	1.000	30.000	90.000	22.400
2.325	13.650	10.160	4.060	.472
.084	36.000	11.590	6.000	3.500
2.500	.200	0.000	0.000	0.000
196.020	.950	.115	12.900	312.000
1100.000	36.000	.472	1.120	7.950
.640	25.580	.010	10.000	5.000
.300	50.000	.500	10.000	.084
1000.000	150.000	16.550	8.000	46.432
31.250	75.000	17.550	21.060	.566
29.677	2204.748	2.182	36.664	2.696
0.000	294.682	1851.537	636.398	0.000
.660	0.000	161.131	115.454	135.947
51.606	186.219	428.346	186.322	11.325
81.073	68.127	4.712	4.650	12.946
0.000	0.000	0.000	0.000	1.000
388.581	216.256	11.590	216.256	331.026
503.010	331.026	186.219	1147.953	1147.612
770.962	830.821	1.029	.743	29.000
.286	1.386	.278	.722	.287
0.000	0.000	50.078	50.078	1.000
2.000	4.470	13.420	1.500	.500
.410	1.270	.381	.041	10.030
.200	.917	.381	1.000	2.000
1.000	50.000	1.051	.113	.041
.113	5.113	5.113	2173.006	342.791
426.912	289.331	40.203	5.000	1.000
5.000				

In order to always be in touch with the solution, a line of 8 numbers in exponential format are always read to the console for every time step. Table 6.5 is the heading for this readout.

Periodically, as determined by the program, if the periodic printout option is on, a more complete readout is made either to the console or to the printer. Table 6.6 shows the heading for this output.

The definition of the metallic nodes called out in Table 6.6 is as follows: (See Figure 4.9.)

1. Around hot space
2. Between heater manifold and heater
3. Between heater and regenerator manifold.
4. Hot end of regenerator
5. Middle of regenerator
6. Regenerator end of cooler

Figure 3.1 gives the nomenclature for this engine.

If the graphic option is on , the following values are displayed to the screen.

A. Scheduled as a function of time
    1. Engine speed up until start of cranking
    2. Vehicle speed

B. Ticks on left hand border of display to show:
    1. Temperature goal for heater metal
    2. Cooling water temperature

C. Plotted as time progresses versus time
    1. Current fuel flow rate (over full height of display) (Starts out at maximum.)
    2. Temperatures on the scale determined by the two ticks
        a. Flue gas leaving heaters and entering air preheater
        b. Average heater metal temperature
        c. Flue gas leaving air preheater
        d. Average of metal around hot spaces
        e. average of metal around hot end of regenerators
        f. average of metal at middle of regenerators
    3. Engine speed on scale determined by specified idle speed
    4. Vehicle speed--compared with desired vehicle speed

D. Pressure-volume work diagrams for the four working spaces. These are on the right side of the screen. Four boxes are drawn. The top box is for working space #1, the second is for working space #2, and so on. Full scale for the pressure is the high pressure gas reservoir. The bottom of each scale is zero pressure.

The temperature plots must be differentiated by comparing the plot with the periodic printout which also contains the same values.

At the end of the program three numbers are displayed. These are:

1. Total fuel consumption, grams
2. Total time, seconds
3. Vehicle speed at end of cycle, m/sec

Table 6.5

HEADING FOR CONSOLE OUTPUT EVERY TIME STEP

Cumulative Time, seconds	Current Fuel Flow, g/sec	Engine Revolutions	Engine Speed, rad/sec	Vehicle Speed, $\frac{\text{meters}}{\text{sec}}$	Desired Vehicle Speed, $\frac{\text{meters}}{\text{sec}}$	Meters Traveled per Engine Revolution	Gear Ratio Flag -1 1st gear or idling 0 2nd gear +1 3rd gear

Table 6.6

HEADING FOR PERIODIC PRINTOUT

Cumulative Time, seconds	Current Fuel Flow, g/sec	Revolutions	Engine Speed, rad/sec	Vehicle Speed, m/sec	Desired Vehicle Speed, m/sec	Time Step, sec			
← Air preheater air temperature, K →									
inlet	in N2	in N3	in N4	in N5	in N6	in N7	in N8	outlet	
← Air preheater metal node temperatures, K →									
N1	N2	N3	N4	N5	N6	N7	N8	Flame Temp., °K	
← Flue gas temperatures, K →									
outlet	out N2	out N3	out N4	out N5	out N6	out N7	out N8	inlet	W.S.
← Engine metal node temperatures, K →						Pressure	Inventory of Gas	Total Volume	
1	2	3	4	5	6	MPa	gr	cm^3	← #1
Hot Space Metal	Hot End of Heater	Cold End of Heater	Hot End Regen.	Middle Regen.	Cold End Regen.	"	"	"	← #2
"	"	"	"	"	"	"	"	"	← #3
"	"	"	"	"	"	"	"	"	← #4
Net Torque N-m	Engine Torque N-m	Vehicle Retarding Torque N-m	Vehicle Inertia Kg m^2	Current Control Constant per sec	Working Gear Ratio m/rev				

There is an error trapping routine in the program which is activated if mass in a working space is changed during Step 4 of the engine torque and internal heat transfer subprogram. Unless some changes are made this routine will not stop the program. If for some reason this routine is activated, the following message is printed out or displayed on the screen:

Flow error is ________ in working space # ____.

Following this is printed out or displayed 8 rows of 7 numbers which help determine where the problem is. The 8 rows are the eight nodes. Within each row the numbers give the following values from left to right.

1. Node number
2. Mass of gas in node at start of time step
3. Mass of gas in node at end of time step
4. Cumulative volumes in the solid
5. Cumulative volumes in the gas
6. Average gas temperature at the start of time step
7. Average gas temperature at the end of time step

7.0 SOLUTION OF BASE CASE

The original expectation was that the solution using the programs described herein could be checked with the steady state power output and efficiency given by General Motors for the 4L23 machine (6). However, this was not done because the engine power output and efficiency were not calculated. It would not be difficult to add both power output calcuation and the efficiency and heat balance calculation since most of the programming has already been done.

The input values for the base case are given in Tables 6.1, 6.2 and 6.3. Based upon this input the periodic output is given on Table 7.1. A line has been drawn to separate the periodic outputs. The key to what these numbers mean is given in Table 6.5.

Figure 7.1 shows the graphical output at the end of the solution of the base case. Figure 7.2 shows the solution part way along to show how the four pressure volume diagrams appear. Figure 7.3 shows how the screen looks with the display every time step superimposed. As an aid to interpreting what is seen on the screen, the data plotted on the screen are also plotted in Figure 7.4 using the data from Table 7.1.

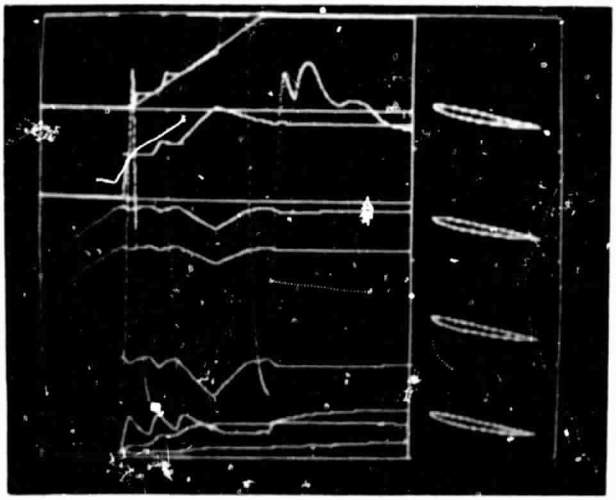

Figure 7.1. Photograph of Complete Graphical Output from Screen (no shift to third gear).

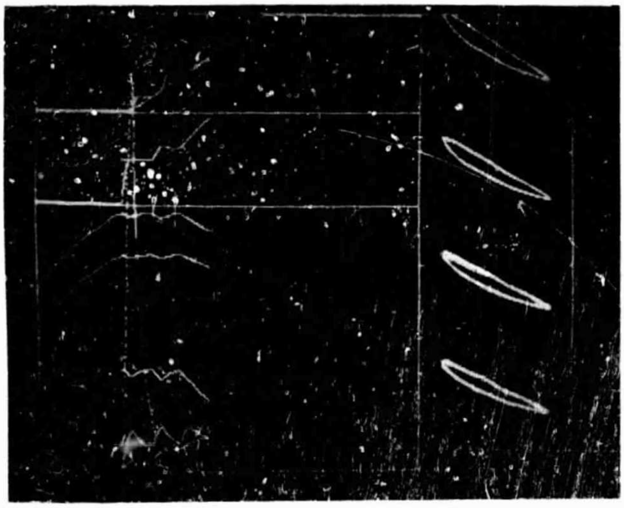

Figure 7.2. Photograph of Graphical Output Part Way Through--Showing PV Diagrams.

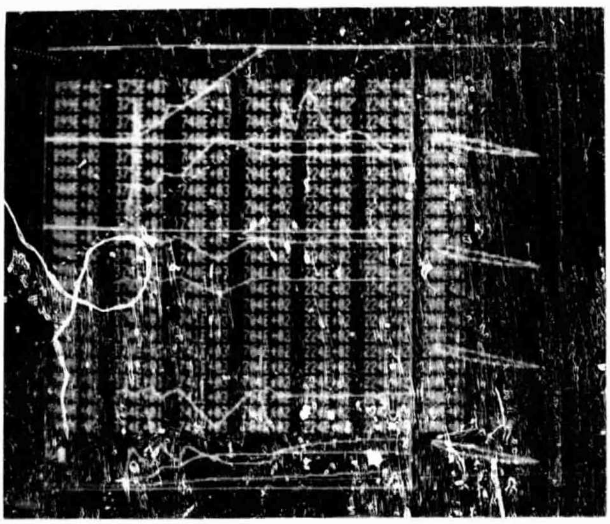

Figure 7.3. Photograph of Final Solution with Display Line for Each Time Step Superimposed. (The display lines can be dimmed out for a better look at the graphics.)

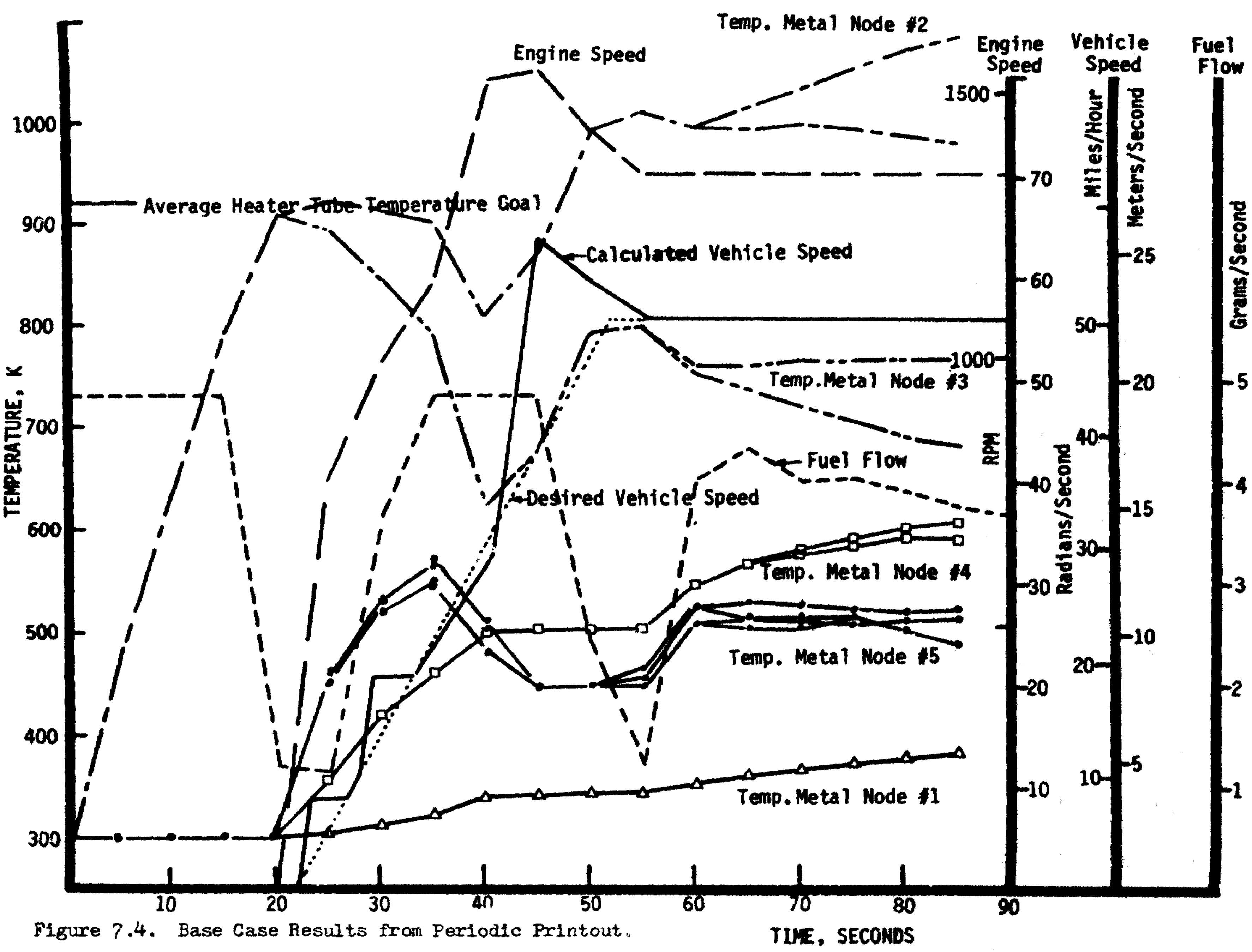

Figure 7.4. Base Case Results from Periodic Printout.

Table 7.1

PERIODIC OUTPUT FOR BASE CASE
(See Table 6.5 for headings)

0.00	0.00	0.00	0.00	0.00	0.00	.50000		
300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
300.00	300.00	300.00	300.00	300.00	300.00	.50	0.00	1147.95
300.00	300.00	300.00	300.00	300.00	300.00	.50	0.00	1147.61
300.00	300.00	300.00	300.00	300.00	300.00	.50	0.00	770.96
300.00	300.00	300.00	300.00	300.00	300.00	.50	0.00	830.82
0.00	0.00	0.00	0.00	0.00	0.00			
5.00	4.85	0.00	0.00	0.00	0.00	.50000		
300.00	318.15	336.15	354.06	371.89	389.67	407.43	425.18	442.92
639.36	654.64	670.85	687.41	704.33	721.64	739.33	756.69	2647.66
1257.62	1285.86	1314.70	1344.11	1374.10	1404.70	1435.90	1467.72	1500.20
300.02	472.73	472.73	300.15	300.02	300.00	.50	0.00	1147.95
300.02	472.73	472.73	300.15	300.02	300.00	.50	0.00	1147.61
300.02	472.73	472.73	300.15	300.02	300.00	.50	0.00	770.96
300.02	472.73	472.73	300.15	300.02	300.00	.50	0.00	830.82
0.00	0.00	0.00	0.00	0.00	0.00			
10.00	4.85	0.00	0.00	0.00	0.00	.50000		
300.00	326.51	352.79	378.92	404.94	430.84	456.65	482.38	507.97
795.60	817.75	841.37	865.20	889.21	913.39	937.67	960.68	2712.72
1394.65	1422.01	1449.62	1477.40	1505.37	1533.51	1561.84	1590.35	1619.11
300.08	639.85	639.85	300.61	300.15	300.00	.50	0.00	1147.95
300.08	639.85	639.85	300.61	300.15	300.00	.50	0.00	1147.61
300.08	639.85	639.85	300.61	300.15	300.00	.50	0.00	770.96
300.08	639.85	639.85	300.61	300.15	300.00	.50	0.00	830.82
0.00	0.00	0.00	0.00	0.00	0.00			
15.00	4.85	0.00	0.00	0.00	0.00	.50000		
300.00	330.65	361.03	391.24	421.30	451.21	481.00	510.65	540.09
872.98	898.51	925.78	953.17	980.59	1008.03	1035.37	1060.95	2744.84
1490.04	1518.22	1546.53	1574.89	1603.29	1631.73	1660.22	1688.76	1717.44
300.19	797.44	797.44	301.35	300.41	300.00	.50	0.00	1147.95
300.19	797.44	797.44	301.35	300.41	300.00	.50	0.00	1147.61
300.19	797.44	797.44	301.35	300.41	300.00	.50	0.00	770.96
300.19	797.44	797.44	301.35	300.41	300.90	.50	0.00	830.82
0.00	0.00	0.00	0.00	0.00	0.00			
20.00	1.23	0.00	0.00	0.00	0.00	.50000		
300.00	333.04	365.76	398.30	430.67	462.88	494.94	526.84	558.47
917.66	944.69	974.02	1003.46	1032.86	1062.21	1091.36	1118.11	2763.22
1558.05	1587.30	1616.65	1646.01	1675.36	1704.71	1734.05	1763.41	1792.89
300.34	913.13	913.14	302.34	300.81	300.00	.50	0.00	1147.95
300.34	913.13	913.14	302.34	300.81	300.00	.50	0.00	1147.61
300.34	913.13	913.14	302.34	300.81	300.90	.50	0.00	770.96
300.34	913.13	913.14	302.34	300.81	300.09	.50	0.00	830.82
0.00	0.00	0.00	0.00	0.00	0.00			
25.01	1.15	38.57	40.33	3.46	2.24	.01250		
300.00	333.99	367.57	400.97	434.20	467.26	500.16	533.88	565.27
935.13	962.01	991.96	1022.14	1052.25	1082.27	1111.91	1138.29	2770.02
1566.28	1595.11	1624.07	1653.90	1681.71	1710.47	1739.16	1767.81	1796.57
304.99	924.00	898.43	357.81	456.71	300.00	.52	.20	726.30
304.88	926.17	900.74	356.51	452.08	300.00	.46	.20	923.89
305.46	924.13	894.79	357.94	457.30	300.00	.31	.20	1204.02
305.49	921.43	893.85	363.28	462.97	300.00	.33	.20	1043.14
4.93	19.26	15.20	8.12	150.00	.54			

Table 7.1 (continued)

30.00	3.69	65.08	51.78	8.24	5.97	.00625		
300.00	334.38	368.39	402.20	435.83	469.29	502.58	535.69	568.46
942.67	970.15	1000.44	1030.93	1061.35	1091.63	1121.46	1148.32	2773.21
1560.40	1588.61	1616.87	1645.02	1673.07	1701.02	1728.85	1756.60	1784.38
313.40	917.97	852.71	422.81	535.62	300.00	.32	.21	1207.25
313.25	919.19	854.04	421.84	535.95	300.00	.35	.21	1032.45
313.76	918.28	849.70	422.66	536.68	300.00	.56	.21	725.12
313.95	915.11	847.62	426.81	536.22	300.00	.46	.20	932.50
-19.78	14.58	34.00	27.86	150.00	1.00			
35.00	4.85	107.32	59.98	9.55	9.70	.00625		
300.00	334.65	368.91	402.97	436.86	470.56	504.10	537.44	570.43
947.67	975.21	1005.69	1036.38	1066.99	1097.44	1127.40	1154.22	2775.18
1550.97	1578.53	1606.09	1633.51	1660.79	1687.91	1714.88	1741.72	1768.56
322.08	907.87	797.43	463.27	576.10	300.00	6.68	4.03	1047.64
321.92	909.84	799.95	463.17	572.46	300.00	10.85	4.05	726.97
322.65	907.56	792.05	460.19	546.10	300.00	9.47	4.08	920.11
322.61	907.32	794.00	462.64	550.74	300.00	6.11	3.97	1202.62
345.28	388.17	37.47	27.86	24.35	1.00			
40.00	4.85	163.33	79.73	12.69	13.44	00625		
300.00	333.80	367.29	400.58	433.70	466.64	499.41	531.99	564.26
931.92	959.76	989.71	1019.71	1049.55	1079.20	1108.46	1135.34	2769.01
1495.55	1521.30	1546.95	1572.40	1597.65	1622.68	1647.51	1672.13	1696.65
339.64	814.13	629.02	501.61	508.94	300.00	7.06	4.22	1020.46
339.62	815.08	629.96	502.08	503.50	300.00	11.09	4.24	724.22
340.09	812.33	624.34	499.32	481.11	300.00	8.85	4.15	942.23
340.10	812.28	625.21	500.17	487.64	300.00	6.15	4.22	1210.42
223.90	277.57	45.43	27.86	112.65	1.00			
45.00	4.85	228.82	80.31	25.56	17.17	.00312		
300.00	333.14	365.98	398.63	431.11	463.42	495.56	527.52	559.19
919.52	947.00	976.43	1005.86	1035.14	1064.23	1092.98	1115.55	2763.94
1511.01	1538.03	1565.03	1591.92	1618.69	1645.34	1671.89	1698.33	1724.77
343.90	877.99	682.94	505.47	450.27	300.00	.46	.22	946.53
343.98	877.04	681.36	505.32	449.55	300.00	.31	.22	1211.63
344.24	875.71	678.97	505.08	450.08	300.00	.36	.22	1015.20
344.25	876.46	680.27	505.21	450.36	300.00	.58	.23	723.97
-190.46	12.71	200.85	111.45	150.00	2.00			
50.00	2.45	290.50	74.86	23.83	20.90	.00312		
300.00	333.96	367.60	401.05	434.33	467.43	500.36	533.12	565.57
934.86	962.81	992.95	1023.14	1053.17	1083.08	1112.67	1139.89	2770.32
1561.71	1590.34	1619.01	1647.60	1676.13	1704.58	1732.97	1761.31	1789.69
345.09	998.30	798.85	506.77	451.87	300.00	.53	.21	742.63
345.17	997.44	797.20	506.25	450.07	300.00	.50	.21	873.30
345.43	996.28	794.97	505.83	449.66	300.00	.33	.21	1178.99
345.44	996.87	796.15	506.23	451.21	300.00	.33	.22	1101.94
-168.17	12.92	181.82	111.45	150.00	2.00			
55.00	1.25	348.11	70.28	22.37	22.40	.00312		
300.00	334.39	368.34	402.10	435.67	469.08	502.30	535.34	567.99
942.81	969.20	999.36	1029.77	1060.09	1090.27	1119.92	1145.65	2772.74
1569.10	1597.70	1626.41	1655.06	1683.62	1712.10	1740.51	1768.85	1797.32
346.90	1014.86	806.89	508.52	458.72	300.00	2.21	1.54	1209.25
346.95	1013.69	805.80	509.85	466.78	300.00	3.04	1.53	867.72
347.25	1012.87	803.18	507.84	456.51	300.00	4.27	1.56	757.28
347.33	1013.49	803.43	506.67	450.35	300.00	3.17	1.65	1063.08
41.91	211.68	166.85	111.45	4.47	2.00			

Table 7.1 (continued)

60.00	4.05	404.21	70.36	22.40	22.40	00312		
300.00	[illegible]	368.94	403.03	436.94	470.67	504.22	537.59	570.62
947.78	975.66	1006.21	1036.91	1067.52	1097.97	1127.97	1155.08	2775.37
1561.54	1589.58	1617.62	1645.55	1673.35	1701.03	1728.58	1756.01	1783.46
355.34	1004.53	770.95	548.53	526.46	300.00	2.18	1.38	1083.28
355.81	997.22	762.55	550.03	526.46	300.00	3.92	1.51	735.51
356.20	994.51	757.97	548.07	513.17	300.00	3.66	1.51	890.08
356.18	996.05	760.00	548.24	515.68	300.00	2.36	1.49	1188.47
7.60	180.18	167.12	111.45	.42	2.00			
65.00	4.34	460.29	70.54	22.45	22.40	.00312		
300.00	334.75	369.16	403.37	437.41	471.27	504.95	538.44	571.62
949.56	978.04	1008.81	1039.62	1070.34	1100.88	1131.04	1158.69	2776.36
1561.57	1589.52	1617.45	1645.26	1672.92	1700.45	1727.83	1755.09	1782.34
362.69	1020.23	765.86	572.01	531.88	300.00	2.75	1.44	913.31
363.48	1007.02	750.92	571.43	519.70	300.00	4.47	1.60	739.03
364.22	997.64	739.41	570.11	509.22	300.00	3.57	1.76	1026.74
364.24	997.91	740.38	571.39	517.36	300.00	2.56	1.77	1218.25
108.95	266.37	167.68	111.45	8.03	2.00			
70.00	4.01	516.41	70.42	22.42	22.40	.00312		
300.00	334.81	369.28	403.56	437.66	471.58	505.32	538.88	572.12
950.75	979.28	1010.13	1041.01	1071.77	1102.36	1132.59	1160.28	2776.87
1563.39	1591.38	1619.34	1647.17	1674.86	1702.40	1729.81	1757.09	1784.36
368.98	1041.90	770.10	586.25	528.73	300.00	3.60	1.37	733.58
369.99	1023.02	749.57	583.42	511.75	300.00	3.63	1.49	895.42
371.04	1003.45	729.19	582.87	508.76	300.00	2.66	1.69	1191.20
371.15	1001.45	727.89	584.64	519.33	300.00	2.73	1.72	1077.16
-16.57	115.58	167.31	111.45	2.42	2.00			
75.00	4.03	572.48	70.44	22.42	22.40	.00312		
300.00	334.85	369.35	403.67	437.80	471.75	505.53	539.11	572.38
951.42	979.95	1010.82	1041.72	1072.51	1103.13	1133.39	1161.06	2777.13
1563.64	1591.61	1619.55	1647.35	1675.02	1702.54	1729.92	1757.17	1784.40
375.04	1058.38	770.33	596.33	523.37	300.00	3.89	1.38	758.27
376.02	1035.64	747.75	592.60	511.42	300.00	2.91	1.49	1064.79
377.21	1006.75	720.16	590.72	511.11	300.00	2.46	1.71	1208.60
377.73	996.31	710.01	592.30	519.25	300.00	3.89	1.92	865.68
-178.78	-28.97	167.37	111.45	3.35	2.00			
80.00	3.92	628.59	70.48	22.43	22.40	.00312		
300.00	334.86	369.39	403.72	437.86	471.83	505.62	539.23	572.51
951.73	980.25	1011.14	1042.09	1072.90	1103.53	1133.78	1161.45	2777.26
1564.20	1592.18	1620.13	1647.95	1675.62	1703.15	1730.54	1757.80	1785.04
380.77	1074.14	771.92	604.42	520.09	300.00	3.11	1.32	936.81
381.62	1048.22	748.73	600.47	516.53	300.00	2.17	1.41	1208.68
382.85	1010.47	714.87	596.19	515.62	300.00	2.80	1.68	1027.25
383.65	990.27	695.60	594.34	506.61	300.00	5.08	1.89	724.59
-197.63	12.56	167.50	111.45	5.40	2.00			
85.00	3.79	684.70	70.41	22.41	22.40	.00312		
300.00	334.89	369.43	403.78	437.94	471.93	505.73	539.35	572.65
952.17	980.63	1011.53	1042.48	1073.29	1103.92	1134.17	1161.81	2777.40
1564.87	1592.85	1620.82	1648.65	1676.34	1703.89	1731.29	1758.57	1785.83
386.01	1088.65	774.78	611.40	521.93	300.00	2.36	1.29	1121.73
386.74	1059.96	750.94	606.75	522.35	300.00	2.06	1.39	1174.29
388.00	1012.45	710.31	599.44	515.42	300.00	3.75	1.66	798.69
388.32	983.92	684.20	592.89	492.24	300.00	4.96	1.87	802.62
8.97	219.10	167.27	111.45	1.96	2.00			

FUEL, TOTT, SPV1 347.416 90.000 22.402

Engine fuel flow = 3.74 g/sec. Engine speed = 70.4 radians/sec. Total engine revolutions = 740.

The identity of the lines on Figure 7.1 can be sorted out by comparing Figure 7.1 with Figure 7.4. Figure 7.4 is much less detailed since it is derived from Table 7.1 for every 5 seconds of real time.

Fuel flow is graphed in Figure 7.1 over the full vertical scale. A smaller scale was used in Figure 7.4. The fuel flow varies widely. It is at its maximum at the start as the engine is heating up and then at two other periods when the engine is working at full capacity. At the end of the driving cycle the fuel flow is still oscillating but appears to be damping out.

The top channel on the left in Figure 7.1 is for vehicle speed. The desired vehicle speed is drawn at the start of the solution. The calculated speed is superimposed upon this ramp and cruise. The calculated speed rushes ahead of the desired speed as the vehicle is put into first, second, and third gear. Possibly the engine has been assigned too much inertia. The vehicle coasts until the speed is back on schedule.

The next channel down on the left of Figure 7.1 is for engine speed. It attains idle speed within the two seconds before getting in hear. As the gear ratio changes in one second, there is very little reduction in engine speed. This is another indication of an unrealisticly high engine inertia.

The final channel on the left is for engine and air preheater temperatures. The order of the temperatures from top to bottom soon after the engine starts are:

1. Flue gas leaving heater and entering preheater.
2. Flue gas leaving preheater.
3. Average heater metal.
4. Average mid-regenerator metal.
5. Average top of regenerator metal.
6. Average hot space metal.

These graphs show that the base case air preheater is inadequate and must be improved. The heater temperature takes a serious dip during second gear but recovers after the shift to third gear. Figure 7.4 shows that the calculated heater temperatures are quite different at the two ends. Half the heat from the burner is made to go to node #2 and half to node #3. There is a wide difference in temperature between these two nodes. Node #3 which is nearest the cold side of the engine is colder. After the engine reaches its cruise speed, there is a slow but pronounced divergence in individual node temperatures for nodes #2 and #3. Other metal node temperatures are less affected. Although data to this detail were only recorded every five seconds of real time, a particular heater node was always consistently high or low or in between. The author currently has no explanation for this behavior.

The next line down in Figure 7.1 has a sawtooth appearance. The temperature of metal node #5 at the midpoint of the regenerator rises when the engine pressure rises and falls when the engine pressure falls. The temperature falls at low pressure because conduction to the cold part of the engine is more important than convection from gas passing through the heater. This node attains its expected temperature midway between the heater and cooler. Note that the plotting of the individual node 5's during the acceleration phase indicates that this temperature cycles over about 50 K during an

engine cycle. Eventually this node temperature is lower than any of those plotted.

The next line in Figure 7.1 starts just below node 5 but is more stable. This is metal node 4 which is at the hot end of the regenerator. It is surprising that this node temperature settles out so close to the middle of the regenerator. This may be due to the low power the engine has to put out during cruise.

The final temperature line in Figure 7.1 is for metal node 1, the metal around the hot space. It starts out the lowest and ends up next to the lowest. One would expect that this node would attain heater temperature. However, at very low load like during cruise, heat conduction to the heat sink draws this temperature way down.

In conclusion, this computer program at this stage in its development gives reasonable looking answers. However, anyone who has worked with large computer programs knows there may be a number of important errors left in these programs.

Finally, the problem of the proper angle increment for the solution has not been resolved. With a 7 to 30 degree angle increment reasonable PV diagrams were drawn. It was feared that since the dead volume of the cooler is so small that with a 7 to 30 degree angle increment much gas might pass through the cooler in one time step without being affected by it. The only way to simulate transient thermal effects is to slow down the solution so that all the gas passing either way is affected by the cooler. To do this efficiently the angle increment limit should be made a variable and its effect should be investigated by a number of complete runs. Since each run takes all day, this work was left for the future.

8.0 CONCLUSIONS AND SUGGESTIONS FOR ADDITIONAL WORK

A computer program has been written and perfected and fully documented that will calculate the transient response of a Siemens arrangement Stirling engine similar to the General Motors 4L23 or the current United Stirling engines. Eighty-two different variables can be changed to adjust the solution to the needs of the calculator and the computer being used and to specify exactly the engine dimension and the operating condition for the engine and the vehicle.

The computer program models an engine which uses working gas pressure as a means of controlling power. The mode of controlling the heater tube temperature and either the engine or vehicle speed is by proportional control.

With this program as a basis the following additional tasks are suggested:

1. Determine the effect of having the four cylinders in unison instead of at 90° phase angle. The calculation normally goes for many hundreds if not thousands of revolutions. The effect on the driving cycle will probably not be significant but calculation speed would be quadrupled.

2. Obtain 16 steady state operating points after the program has been modified to have averaged power output and efficiency over a specified time period. Compare with a standard and make adjustment in the dimensions or other parameters.

3. Adapt the program to prediction of the transient performance of the Department of Energy Mod I engine in the vehicle that is planned for it. This will require finding all dimensions including thermal conductivities, moment of inertia, seal and mechanical friction, etc.

4. Compare this program and the version proposed in #1 above to that program published by Daniele and Lorenzo (4). Compare on the basis of solution time and accuracy.

5. Adapt either the current program or the one cylinder modification (#1 above) to a calculated, realistic heat transfer in all gas spaces. That is, the hot and cold spaces would not always be adiabatic and the heat exchangers would have the heat transfer coefficients expected for the instantaneous flow. Show how the gas and metal temperatures vary during the cycles.

6. Add variable stroke control to the program.

7. Predict the transient and steady state response of the Advenco engine now at NASA-Lewis.

This computer program was developed on a good quality microcomputer with high resolution graphic capabilities. With only the graphic output plus the single time display per time step the full base case of 90 seconds real time was run in 3 hours 45 minutes. The graphic display plus the printouts if desired would be adequate record of how well a particular method of control worked.

the single time display per time step the full base case of 90 seconds real time was run in 3 hours 45 minutes. The graphic display plus the printouts if desired would be adequate record of how well a particular method of control worked.

9.0 REFERENCES

1. Prototype Vehicle Performance Specifications, EPA, Ann Arbor, MI, 3 Jan 1972.

2. W. Kay, A.L. London, "Compact Heat Exchangers," Second Edition, p. 126.

3. W.H. McAdams, "Heat Transmission," Third Edition, p. 273.

4. C.J. Daniele and C.F. Lorenzo, "Preliminary Results from a Four-Working Space, Double-Acting Piston, Stirling Engine Control Model," DOE/NASA/1040-17, NASA TM-81569.

5. See W.R. Martini, "Stirling Engine Design Manual, "DOE/NASA/3152-78/1, NASA CR-135382, April 1978, p. 113.

6. W.R. Martini, "Validation of Published Stirling Engine Design Methods Using Engine Characteristics from the Literature," 1980 IECEC Record, pp. 2245-2250.

APPENDIX A

TEST PROGRAM, WARM.FOR

Introduction

It was found that in order to perform a 90 second simulation of a simple driving cycle, it was necessary to repeat the calculation scheme approximately 35,000 times. The burner simulation is a significant part of the calculation scheme. No only does it account for about one-fifth of the program lines, it also includes Z subroutine calls and multiple use of the exponential and log functions, all of which cause the computer to spend a large percentage of its executive time in this area. In order to reduce the 8 hour executive time required by the Altos computer and to simplify the main program, it was decided to attempt to create the WARM.FOR program. WARM.FOR would include the burner simulation from CNTLB.FOR, and would hopefully generate a simple relationship between burner efficiency and heat required by the heater tubes. CNTLB.FOR would then require only a few equations to preduct fuel consumption as a function of engine heat requirement.

Node Arrays

One of the first modifications to the burner simulation was to increase the number of calculation nodes of the air preheater. Originally only four nodes were accounted for, but it was decided to use arrays instead of single variables. Tests were performed to determine the accuracy or the burner efficiency as a function of the number of nodes used in the calculation. It was found that by using 20 nodes, the calculated burner efficiency was within .5% of the efficiency calculated using 99 nodes. When using 99 nodes, the simulation requires 66% more time than the 20 node simulation requires. It was decided the ½ percent was not worth the prolonged calculation time. The four node simulation was about 7.5% low so the 20 node simulation was used as a good compromise.

Time Increment

Regardless of the size of the program, if the calculations need to be executed twice as many times, then the time requirement doubles. A test was performed to determine how often burner calculations had to be made so that reasonably accurate numbers would be generated. It was found that by using .05, .1, and .5 second increments, the calculated burner efficiencies agree to ½ percent. However, when the one second time increment was used, the numbers generated became erratic and efficiencies of over 100% were calculated. As a result it was recommended that a .5 second time increment be used.

The results of the time increment and metal node test are shown in Table A1. A sample table generated by WARM.FOR for 20 nodes and .5 second increment is shown in Table A2.

Table A.1

BURNER EFFICIENCY AT START AND END OF 90 SECOND HEAT LOADS
(20 second warm-up)

CALCULATION NODES IN AIR PREHEATER METAL

Nodes	Load	.05 sec Start	.05 sec End	.1 sec Start	.1 sec End	.5 sec Start	.5 sec End	1 sec Start	1 sec End
2 Nodes	2500 W	70.9352	74.2632	70.9352	74.2863	70.9466	74.3302	115.7146	80.2283
	5000 W	56.6832	64.9165	56.6898	64.926	56.6207	64.9326	56.7153	65.0361
4 Nodes	2500 W	73.7399	79.5016	73.7245	79.5016	73.6107	79.4766	304	139
	5000 W	61.0833	72.2304	61.0749	72.2393	60.9241	72.2423	63.1280	73.2075
8 Nodes	2500 W	75.5816	83.6796	75.5557	83.6637	75.3073	83.6161	1135	158
	5000 W	63.4412	75.8708	63.4367	75.8806	63.2468	75.8790	65.5192	76.8893
16 Nodes	2500 W	76.4958	85.9670	76.4826	85.9628	76.1591	85.9000	349	--
	5000 W	64.2311	77.0706	64.2264	77.0773	64.0225	77.0773	--	--

CALCULATION TIME INCREMENT

Table A.1 (continued)

BURNER EFFICIENCY AT START AND END OF 2 CONSECUTIVE 90 SECOND HEAT LOADS
(20 second warm-up)

CALCULATION NODES IN AIR PREHEATER METAL		.1 sec Start	.1 sec End	.5 sec Start	.5 sec End
25 Nodes	2500 W	76.7254	86.5872	76.3899	86.5277
	5000 W	64.3823	77.3290	64.1774	77.3273
35 Nodes	2500 W	76.8156	86.8258	76.4726	86.7613
	5000 W	64.4340	77.4155	64.23	77.4155
45 Nodes	2500 W	76.8557	86.9199	76.5091	86.8600
	5000 W	64.4564	77.4495	64.2498	77.4512
64 Nodes	2500 W			76.5357	86.937
	5000 W			74.2662	77.45

CALCULATION TIME INCREMENT

Table A.2

WARM.FOR OUTPUT

20 Nodes

.5 sec Time Increment

TIME(SEC)	HT TUBE (K)	FUEL FLOW(G/S)	HEAT REQ(W)	BURNER EFF%	APH MET NODE	APH HT BAL%
.50	300.0000	10.0000	0.0000	0.0000	324.5556	100.0000
10.00	615.9132	10.0000	0.0000	0.0000	729.4293	-154.5814
20.00	914.6870	1.5026	0.0000	0.0000	1051.0254	-169.0996
30.00	920.7886	.2823	2500.0000	76.2974	1115.6749	-46.4059
40.00	920.8254	.2749	2500.0000	78.3437	1171.0699	-42.2901
50.00	920.8550	.2690	2500.0000	80.0645	1215.6971	-39.1455
60.00	920.8789	.2642	2500.0000	81.5145	1252.1597	-36.6771
70.00	920.8987	.2603	2500.0000	82.7533	1282.3420	-34.6875
80.00	920.9153	.2569	2500.0000	83.8227	1307.6326	-33.0490
90.00	920.9293	.2541	2500.0000	84.7447	1329.0554	-31.6823
100.00	920.9414	.2517	2500.0000	85.5626	1347.4222	-30.5140
110.00	920.9518	.2496	2500.0000	86.2739	1363.2985	-29.5149
120.00	918.8409	.6718	5000.0000	64.1167	1439.2318	-82.4510
130.00	918.9671	.6466	5000.0000	66.6189	1508.0140	-73.6010
140.00	919.0687	.6262	5000.0000	68.7810	1565.0101	-66.7919
150.00	919.1521	.6096	5000.0000	70.6625	1612.8295	-61.3918
160.00	919.2214	.5957	5000.0000	72.3074	1653.4080	-57.0034
170.00	919.2801	.5840	5000.0000	73.7599	1688.1996	-53.3576
180.00	919.3303	.5739	5000.0000	75.0511	1718.3132	-50.2730
190.00	919.3735	.5653	5000.0000	76.1985	1744.6046	-47.6269
200.00	919.4114	.5577	5000.0000	77.2326	1767.7417	-45.3196

Burner Correlation

In order to simplify the burner calculations for the CNTLB.FOR program, two correlations were necessary:

1. burner efficiency as a function of engine heat requirement.
2. burner efficiency as a function of time after the heat requirement changes significantly (transient condition).

The second correlation was attempted first, using WARM.FOR a 1000 second duration. The burner efficiency was calculated as a function of time for a 20 second warm up and one constant heat requirement. Three points were taken from the first 100 seconds of simulation and an effort was made to discover a function described by the three points that would indicate the burner efficiency at 1000 seconds. Two methods were used, a power curve fit using the HP-67 curve fitting routine and a more direct method involving the solving of three simultaneous equations with three unknowns. The results are shown in Figure A.1. A non-linear extrapolation of this size is, of course, very difficult. Since the closest correlation was 2% off for this simple example, it was decided that the burner calculations should be an integral part of the main control program (CNTLB.FOR) if any reasonable accuracy is desired.

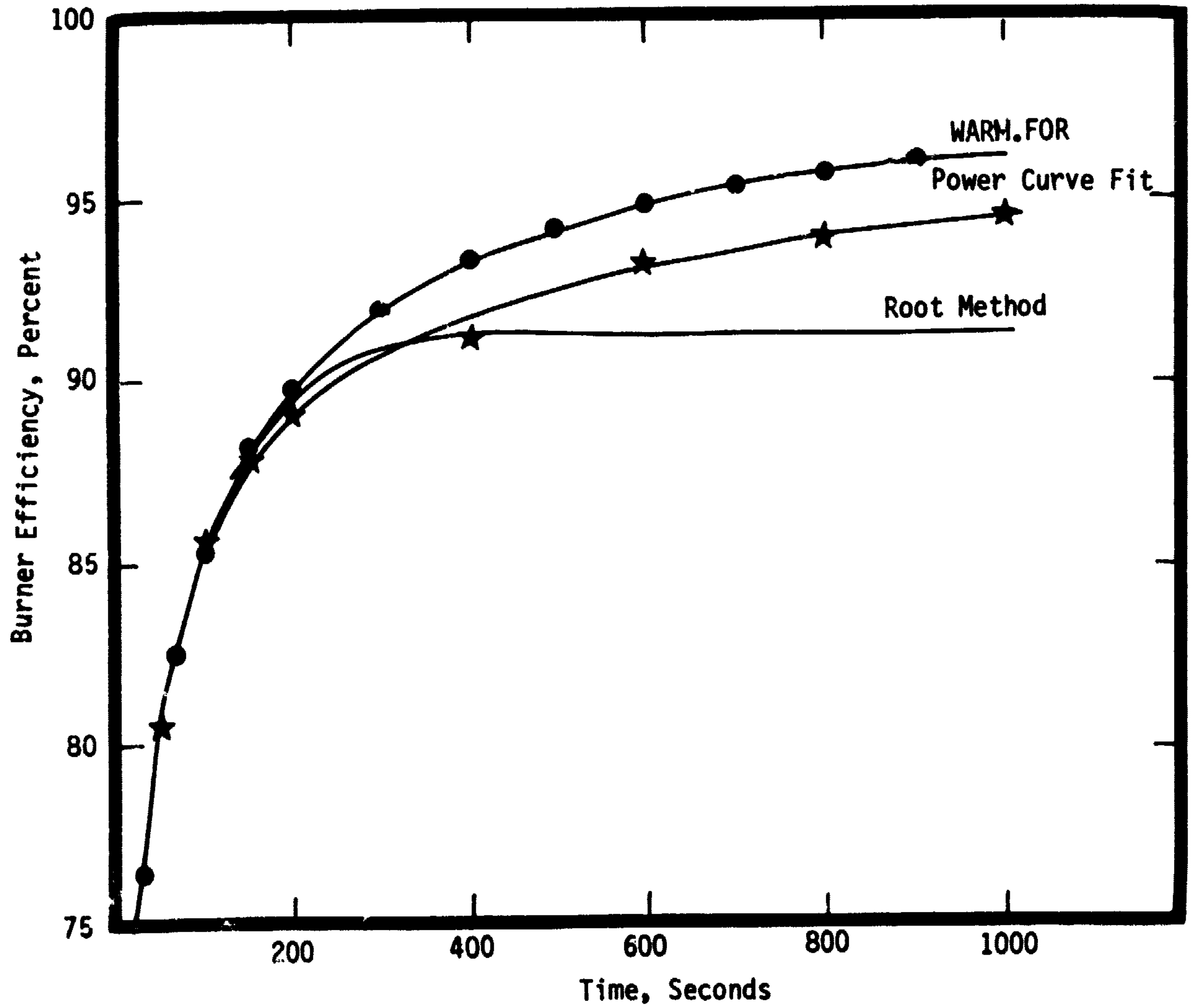

Figure A.1. Burner Efficiency Versus Time.

Utility of WARM.FOR

Although WARM.FOR cannot be used to generate a simple correlation for use in CNTLB.FOR, it can be used to determine burner efficiencies and air preheater temperatures as a function of time for various heat requirements. Of most value are the plots of various burner temperatures and burner efficiency as a function of time. A worthwhile addition to the program would be to calculate the heat requirement of the other metal parts of the engine as warm up occurs.

Input

A sample table and the glossary of input variables are shown in Table A3. Changes are made by typing the item number, a space, then the new value, including a decimal point. Q1 is assigned the value of 1 if a table output such as Table A2 is desired. DTO determines the frequency of data printout. TTT is the duration of each heat requirement. The heat requirement is set during the warm up time, and is increased by HREQ each time a period lasting TTT seconds is finsihed. The simulation lasts TOTT seconds. Hash marks divide the total simulation time into tenths.

Graphical Output

A diagram of a typical graphical output is shown in Figure A.2. The top section plots various burner temperatures. The bottom section plots burner efficiency and fuel flow as a function of maximum fuel flow. The left side of the screen displays digital values of what is presented graphically on the right side. The air preheater balance (APH BAL) describes the balance of energy between heat transfer from the flue gas to the air preheater metal and heat transfer from the air preheater metal to the inlet gas. A negative balance indicates that more heat is being transferred to the metal than from the metal, so its temperature must be rising.

Program Listing

The program listing of WARM.FOR now follows. Note that the listing contains its own nomenclature and its own method of changing input variables similar to CNTLA given in the body of the report.

Table A.3

WARM.FOR SAMPLE TABLE AND GLOSSARY OF TABLE VARIABLES

```
******************************************************************************
* OPERATING CONDITIONS BY NUMBER              *              *               *
* 01  922.200 * 02    50.000 * 03  300.000 * 04      .500 * 05    10.000 *
* 06   20.000 * 07   20       * 0810000.000 * 09    90.000 * 10   200.000 *
* 11    1     * 12   10.000 * 13     0.000 * 14     0.000 * 15     0.000 *
* 16    0.000 * 17    0.000 * 18     0.000 * 19     0.000 * 20     0.000 *
* ENGINE DIMENSIONS           *              *              *               *
* 21   10.000 * 22    5.030 * 23  200       * 24      .100 * 25      .300 *
* 26   16.550 * 27     .640 * 28      .472 * 29    25.580 * 30  [illegible] *
* 31    2.500 * 32      200 * 33    8       * 34      .000 * 35     0.000 *
* 36    0.000 * 37    0.000 * 38     0.000 * 39     0.000 * 40     0.000 *
******************************************************************************
II XXXXXXXXXX           TYPE 48 TO END      TYPE 49 TO EXECUTE NEW CASE
```

1. THMG, °K
2. TPB, °K
3. T1, °K
4. DT, sec
5. FFF, g/s
6. THU, sec
7. NO
8. HREQ, watts
9. TTT, sec
10. TOTT, sec
11. Q1
12. DTO, sec

21. LAPH, cm
22. WAPH, cm
23. NAPH
24. TMAPH, cm
25. TAPH, cm
26. RAF
27. DOH, cm
28. DIH, cm
29. LHH, cm
30. NTH
31. LR, cm
32. FF
33. NS
34. MSH, wires/cm

```
Inlet Air Temp.
          Cold Node         Hot Node
 300.  ********************   481.
       *                  *   Flame Temp.
       *535.    615.   729. *       2685.
       *                  *
1472.  ********************  2297.
 Exhaust Temp.
BURN EFF  0.0 APH BAL-464.6 CFF 10.000


 300.  ********************   962.
       *                  *
       *694.    843.  1051. *       3166.
       *                  *
 791.  ********************  2232.

BURN EFF  0.0 APH BAL-169.1 CFF  1.503


 300.  ********************  1089.
       *                  *
       *653.    844.  1116. *       3294.
       *                  *
 675.  ********************  1610.

BURN EFF 76.3 APH BAL -46.4 CFF   .282


 300.  ********************  1136.
       *                  *
       *619.    845.  1171. *       3341.
       *                  *
 649.  ********************  1612.
```

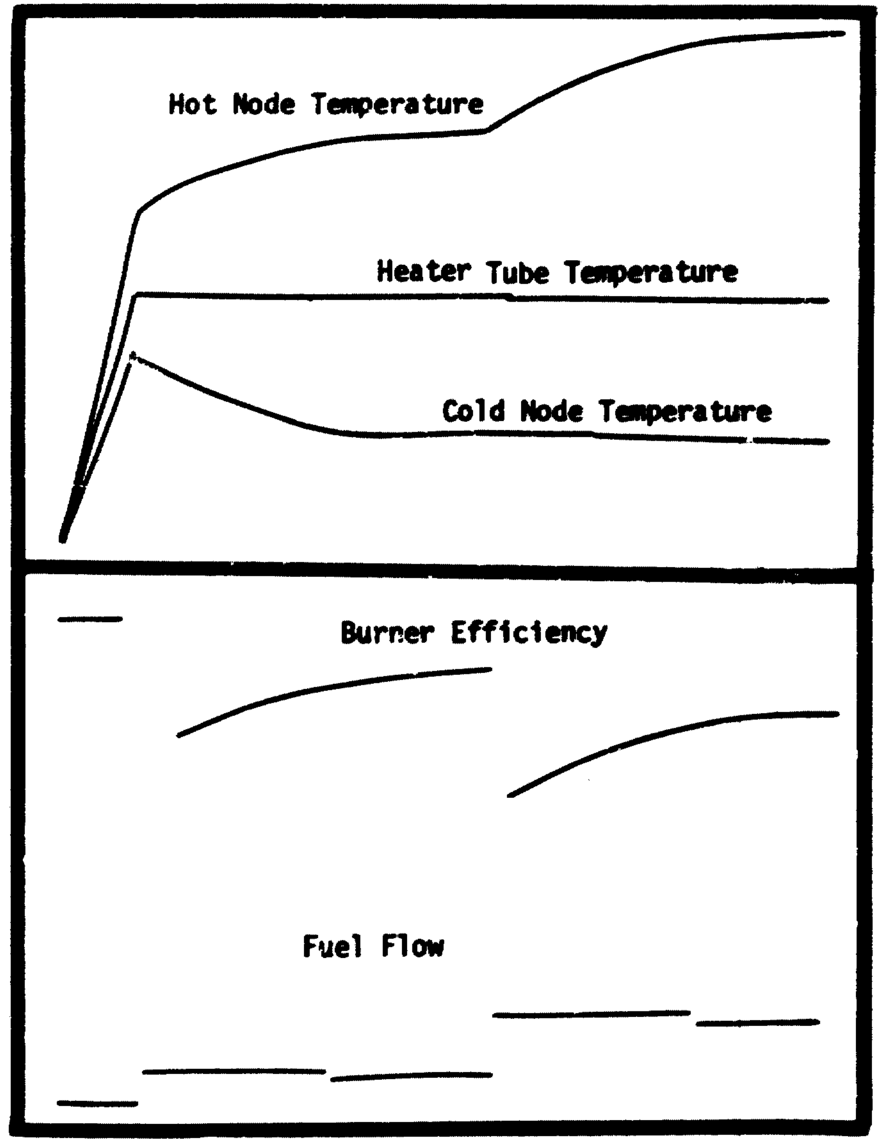

Figure A.2. Sample Graphics Screen.

```
C PROGRAM WARM.FOR     PRE-PROGRAM FOR CNTL.FOR
C WRITTEN BY MARTINI ENGINEERING UNDER CONTRACT NUMBER
C DEN3-226 FOR NASA-LEWIS UNDER THE DOE ADVANCED AUTOMOTIVE
C PROPULSION PROGRAM
C          ***** NOMENCLATURE *****
C     A = TEMPORARY VARIABLE
C     AAPH = HEAT TRANSFER AREA OF FULL AIR PREHEATER, SQ CM
C     ACE = RADIAL ENGINE ACCELERATION, RAD/SEC**2
C     ACV = ACCELERATION OF VEHICLE AT START OF TIME STEP, M/SEC**2
C     ACY = PI4*DCY**2
C     AF = AIR FRICTION, NEWTONS
C     AFR = FRONTAL AREA OF VEHICLE, M**2
C     AH = HEAT TRANSFER AREA FROM FLAME, FULL ENGINE, SQ CM
C     AMF = GAS HEATER MINIMUM FLOW AREA, CM**2
C     B = TEMPORARY VARIABLE
C     BAL = AIR PREHEATER ENERGY BALANCE, (HTA-HTF)/HTA, %
C     BCY = PI4*(DCY**2-DDR**2)
C     BEF = BURNER EFFICIENCY, %
C     CCY = ACY-BCY
C     CFF = CURRENT FUEL FLOW, G/S
C     CMAPH = HEAT CAPACITY OF FULL AIR PREHEATER, J/K
C     CMH = HEAT CAPACITY OF GAS HEATERS FOR ONE CYLINDER, J/K
C     CMX = HEAT CAPACITY OF REGENERATOR MATRIX, J/K
C     CP = HEAT CAPACITY AT CONSTANT PRESSURE, J/G K
C     CPA = HEAT CAPACITY OF AIR, J/G K
C     CPFG = HEAT CAPACITY OF FLUE GAS, J/G K
C     CS = COEFFICIENT FOR SHAPE OF VEHICLE
C     CV = HEAT CAPACITY AT CONSTANT VOLUME, J/G K
C     CYY = 4.*CZ*DT/CMAPH
C     DANG = CHANGE IN ENGINE ANGLE, RAD
C     DCY = DIAMETER OF CYLINDER, CM
C     DDR = DIAMETER OF DRIVE ROD, CM
C     DEQ = EQUIVALENT DIAMETER (USED IN AIR PREHEATER), CM
C     DIC = DIAMETER INSIDE OF COOLER TUBES, CM
C     DIH = DIAMETER INSIDE OF HEATER TUBES, CM
C     DIST = DISTANCE TRAVELED FROM START, M
C     DOH = OUTSIDE DIAMETER OF HEATER TUBES, CM
C     DR = DIAMETER OF EACH REGENERATOR, CM
C     DST = DISTANCE TRAVELED DURING TIME STEP, M
C     DT = TIME STEP, SEC
C     EADEG = ENGINE ANGLE, DEGREES
C     EARAD = ENGINE ANGLE, RADIANS
C     EIN = ENGINE INERTIA, N-M**2
C     EX(20) = AIR PREHEATER METAL NODE TEMPERATURES, K
C     FCA = FRACTION OF VCDX THAT IS ADIABATIC
C     FF = FILLER FACTOR, FRACTION OF REGENERATOR VOLUME FILLED
C          WITH SOLID, MUST BE ZERO IF IT IS NOT USED
C     FFF = FULL FUEL FLOW, G/S
C     FLAME = BURNER FLAME TEMPERATURE, K
C     FP(4) = FORCE ON PISTONS(AWAY FROM CRANKSHAFT IS POSITIVE)
C             NEWTONS
C     FUEL = TOTAL FUEL CONSUMED BY ENGINE, G
C     FWI = FLOW, WATER INLET FOR ENTIRE ENGINE, G/SEC
```

```
C     GA = (KK-1)/KK
C     GAPH = MASS VELOCITY (USED IN AIR PREHEATER), G/S CM**2
C     GMAX = MAXIMUM MASS VELOCITY IN HEATER, G/S CM**2
C     HAS = HEAT TRANSFER COEFFICIENT, W/K CM**2
C     HREQ = ENGINE HEAT LOAD, WATTS
C     HTA = HEAT RECEIVED BY ENTERING AIR, J/G
C     HTG = HEAT REJECTED BY FLUE GAS, J/G
C     IG1 = VEHICLE CONTROL FLAG, 1=REMOVE MASS 2=ADD MASS
C     I1,I2 = GRAPHIC OUTPUT, X VALUES
C     J1,J2 = GRAPHIC OUTPUT, Y VALUES
C     J7 = DETERMINES INPUT NUMBER SELECTION
C     KAR = COEFFICIENT OF AIR RESISTANCE
C     KK = CP/CV
C     KR = 1 / KK
C     KRR = COEFFICIENT OF ROLLING RESISTANCE
C     LAPH = HEAT TRANSFER LENGTH IN AIR PREHEATER, CM
C     LC = LENGTH OF COOLER TUBES, CM
C     LCR = LENGTH OF CONNECTING ROD, CM
C     LH = LENGTH OF HEATER TUBES, CM
C     LHH = HEATED LENGTH OF HEATER TUBES, CM
C     LHV = LOWER HEATING VALUE OF FUEL, J/G
C     LR = LENGTH OF REGENERATOR, CM
C     M(4) = INVENTORY OF GAS IN EACH ENGINE COMPARTMENT, G
C     ME = ENGINE MECHANICAL EFFICIENCY, PERCENT
C     MGI = INITIAL GAS INVENTORY, G
C     MIR = FACTOR RELATING MASS FLOW TO PRESSURE DROP, G/S MPA
C     MIR1 = ADJUSTMENT OF MIR TO PREVENT CONTROL OVERSHOOT
C     MIV = MASS, INERTIA OF VEHICLE, KG
C     MSH = MESH SIZE, WIRES/CM
C     MW = MOLECULAR WEIGHT OF WORKING GAS, G/G MOLE
C     MWFG = MOLECULAR WEIGHT OF FLUE GAS, G/G MOLE
C     NAPH = # OF AIR PREHEATER FLOW PASSAGES IN EACH DIRECTION
C     NR = NUMBER OF REGENERATORS/CYLINDER
C     NS = NUMBER OF SCREENS PER REGENERATOR
C     NTC = NUMBER OF COOLER TUBES/CYLINDER
C     NTH = NUMBER OF HEATER TUBES PER COMPARTMENT
C     OM1 = DESIRED IDLE SPEED OF ENGINE, R/S
C     PI = PI = 3.141592654
C     PI2 = PI/2 = 1.5070796327
C     PI32 = 3*PI/2
C     PI4 = PI / 4 = .7853981635
C     PRH = HIGH PRESSURE RESERVOIR PRESSURE, MPA
C     PRL = LOW PRESSURE RESERVOIR PRESSURE, MPA
C     P1(4) = GAS PRESSURE AT BEGINNING OF TIME STEP, MPA
C     P2(4) = GAS PRESSURE AFTER VOLUME CHANGE, MPA
C     P3(4) = GAS PRESSURE AFTER TEMPERATURE EQUILIBRATION AT
C                 CONSTANT VOLUME, MPA
C     P4(4) = COMMON GAS PRESSURE AT END OF TIME STEP, MPA
C     QE = HEATING OF HEATER TUBES OF ONE CYLINDER BY BURNER
C           DURING A TIME STEP, J
C     QEX = HEATING OF WORKING GAS IN HEATER TUBES DURING TIME STEP,J
C     QHI(4) = CUMULATIVE HEAT INPUT FOR CYCLE, J
```

```
C     Q1 = OUTPUT FLAG, 1=FULL OUTPUT  2=QUICK RUN
C     R = 8.314 J/G MOL K
C     RAD = 0.017453 RADIANS/DEGREE
C     RAF = RATIO OF AIR TO FUEL, G/G
C     RA1 = RAF+1, G/G
C     RC = RADIUS OF CRANK, CM
C     RC2 = 2*RC
C     RE = REYNOLDS NUMBER
C     RF = ROLLING FRICTION, NEWTONS
C     RGE = RATIO OF GEARS, VEHICLE TRAVEL/REV, METERS
C     RX = CP - CV
C     SPM = CRUISING SPEED OF VEHICLE, M/S
C     SPVD = VEHICLE SPEED DESIRED BY SCHEDULE, M/S
C     SPV1 = SPEED OF VEHICLE AT BEGINNING OF TIME STEP, M/SEC
C     SS = CHECK TO ALLOW USER CHANCE TO STOP
C     ST = 1 TO CONTINUE, 2 TO START OVER
C     STN = STANTON NUMBER TIMES PRANDL NUMBER TO TWO THIRDS POWER
C     T1 = AMBIENT AIR TEMPERATURE, K
C     TA = AVERAGE OF HEATER METAL TEMPERATURES, K
C     TAC = VEHICLE ACCELERATION TIME, SEC
C     TAPH = THICKNESS OF PREHEATER PASSAGE, CM
C     TCR = DURATION OF STARTING MOTOR TORQUE, SEC
C     TGC(2,4) = TEMPERATURE OF GAS IN COOLER, K
C     TGCS(2,4) = TEMPERATURE OF GAS IN COLD SPACE AND DUCT, K
C     TCM(4) = TEMPERATURE OF COLD METAL IN COOLER, K
C     TF = TIME INCREMENT FLAG, 0=DOUBLE INCREMENT, 1=NO CHANGE,
C          2=HALF INCREMENT
C     TGH(2,4) = TEMPERATURE OF GAS IN HEATER, K
C     TGHS(2,4) = TEMPERATURE OF GAS IN HOT SPACE, K
C     TGR(2,4) = TEMPERATURE OF GAS AT REGENERATOR MIDPOINT, K
C     THW = THICKNESS OF WIRE IN SCREENS OF REGENERATOR, CM
C     THM(4) = TEMPERATURE OF HOT METAL IN HEATER, K
C     THMG = TEMPERATURE, HOT METAL GOAL, K
C     THU = ENGINE WARM-UP TIME, SEC
C     TID = IDLE TIME AFTER CRANKING, SEC
C     TIN(20) = INLET BURNER AIR NODE TEMPERATURES, K
C     TI1 = THU+TCR
C     TI2 = TI1+TID
C     TI3 = TI2+TAC
C     TMAPH = THICKNESS OF METAL SEPARATING EACH FLOW PASSAGE, CM
C     TMR(4) = MIDPOINT TEMPERATURE OF REGANERATOR MATRIX, K
C     TNET = NET ENGINE TORQUE, N-M
C     TOTT = TOTAL SIMULATION TIME, SEC
C     TOU(20) = FLUE GAS NODE TEMPERATURES, K
C     TPB = TEMPERATURE, PROPORTIONAL BAND IN HOT METAL, K
C     TPO = INTERVAL BETWEEN PRINT OUTS, S
C     TQ(4) = TORQUE FROM EACH PISTON, CCW IS POSITIVE, N-M
C     TQI = TOTAL INDICATED TORQUE, N-M
C     TQS = TOTAL SHAFT TORQUE, N-M
C     TQV = TORQUE VEHICLE PUTS ON ENGINE, N-M
C     TRAV = AVERAGE REG. METAL TEMP, K
C     TST = STARTING MOTOR TORQUE, N-M
```

```
C     TT = CHECK TO DETERMINE WHEN POINTS SHOULD BE PLOTTED
C     TWI = TEMPERATURE, WATER INLET, K
C     TWO = TEMPERATURE OF COOLING WATER, K
C     UAPH = HEAT TRANSFER COEFF. AIR TO METAL IN AIR PREHEATER  W/CM2 K
C     UH = HEAT TRANSFER COEFF. FLUE GAS TO GAS HEATER METAL, W/CM2 K
C     UXX = UY/CY
C     VAB = VOLUME OF AIR IN BURNER, CU CM
C     VCA(2,4) = VOLUME, COLD, ADIABATIC, START AND END OF TIME STEP
C     VCA1(4) = VOLUMES OF GAS ORIGINALLY IN ADIABATIC COLD SPACE
C               AFTER VOLUME CHANGE, CU CM
C     VCDA = VOLUME, ADIABATIC COLD DEAD, CU CM
C     VCD = VOLUME, ISOTHERMAL COLD DEAD, CU CM
C     VCD(4) = VOLUMES OF GAS ORIGINALLY IN GAS COOLER AND
C                ISOTHERMAL PART OF COLD DUCT AFTER VOLUME CHANGE
C     VCDX = VOLUME, COLD DEAD NOT IN GAS COOLER, CU CM
C     VHA(2,4) = VOLUME, HOT, ADIABATIC,START AND END OF TIME STEP
C     VHA1(4) = VOLUMES OF GAS ORIGINALLY IN HOT ADIABATIC SPACE
C               AFTER VOLUME CHANGE, CU CM
C     VHD = VOLUME, HOT DEAD, (ASSUMED ISOTHERMAL) CU CM
C     VHD1(4) = VOLUMES OF GAS ORIGINALLY IN HOT DEAD SPACE AFTER
C               VOLUME CHANGE, CU CM
C     VHDX = EXTRA HOT VOLUME BESIDES THAT IN THE GAS HEATER,
C           CU CM, INCLUDES END CLEARANCE, GAP AROUND HOT CAP
C           AND MANIFOLD ASSUMED AT HOT METAL TEMPERATURE
C     VRD = VOLUME, REGENERATOR DEAD, PER CYLINDER, CU CM
C     VRD1(4) = VOLUMES OF GAS ORIGINALLY IN REGENERATOR AFTER VOLUME
C               CHANGE, CU CM
C     VT(2,4) = TOTAL GAS VOLUMES AT START AND END OF TIME STEP, CU CM
C     VTD = TOTAL DEAD VOLUME, CU CM
C     WAPH = WIDTH OF EACH AIR PREHEATER PASSAGE, CM
C     WCA(2) = MASS IN ADIABATIC COLD SPACE AT START AND END, G
C     WCD(2,4) = MASS IN ISOTHERMAL COLD SPACE AT START AN END, G
C     WHA(2,4) = MASS IN ADIABATIC HOT SPACES AT START AND END, G
C     WHD(2,4) = MASS IN HOT DEAD SPACE, G
C     WRC = MASS OF REGENERATOR GAS MOVING INTO COOLER, G
C     WRD(2,4) = MASS IN REGEN. DEAD SPACE AT START AND END, G
C     WRH = MASS OF REGENERATOR GAS MOVING INTO HEATER, G
C     X = TEMPORARY VARIABLE
C     XA = LCR**2
C     XB = LCR - RC
C     XC = R / MW
C     XX(4) = OLD/NEW VOLUME RATIO
C     X1 = ENGINE SPACINGS IN 4 CYLINDER MACHINE
C     X2 =   "      "      " "   "        "
C     X3 =   "      "
C     X4 =   "      "
C     XY = EXP(-UXX/CYY), ZERO FOR SLOW AIR FLOW THROUGH PREHEATER
C     Y = TEMPORARY VARIABLE
C     YY = TEMPORARY VARIABLE
C     Z = FLAG FOR WORKING FLUID, 1 FOR H2, 2 FOR HE, 3 FOR AIR
C     ZZ = TEMPORARY VARIABLE
C        ***** START OF PROGRAM *****
```

```
      DIMENSION THM(4),TCM(4),TGH(2,4),TGC(2,4),TIN(50),
     1 EX(50),TOU(50),TMR(4),QHI(4),T3A(4)
      INTEGER Q1,ST
      REAL LH,LR,LC,MWFG,LAPH,LHH,LHV,MSH
C  INITIAL OPERATING CONDITIONS
      DATA THMG,TPB,DT,MWFG/922.2,50.,0.5,28.63/
      DATA LHV,FFF,VAB,RAF,TPO/46432.,10.,3000.,16.55,10./
      DATA CPA,CPFG,T1,TTT,TOTT/1.03,1.20,300.,90.,200./
      DATA THU,NO,GN,HREQ,Q1/20.,20,0.0,10000.,0/
C  ENGINE DIMENSIONS
      DATA DCY,DOR,NS/10.16,4.06,0/
      DATA VHDX,DIH,LH,NTH/11.59,0.472,41.48,36/
      DATA NR,DR,LR,FF/6,3.5,2.5,.2/
      DATA DOH,LHH,TMAPH/.640,25.58,.1/
      DATA LAPH,WAPH,TAPH,NAPH/10.,5.,.3,200/
C  DATA CONSTANTS
      DATA PI4,PI,PI2,RAD,R/0.7854,3.14159,1.57080,0.017453,8.314/
      DATA J,RGE/5,.54/
9     WRITE(J,10)
10    FORMAT(//////'0',71('*')/' * OPERATING CONDITIONS BY NUMBER
     1',10X,'*',13X,'*',13X,'*')
      WRITE(J,12)THMG,TPB,T1,DT,FFF,THU,NO,HREQ,TTT,TOTT
12    FORMAT(' * 01',F9.3,' * 02',F9.3,' * 03',F9.3,' * 04',F9.3,
     1' * 05',F9.3,' *'/' * 06',F9.3,' * 07',I5,5X,' * 08',F9.3,' * 09',
     2F9.3,' * 10',F9.3,' *')
      WRITE(J,14)Q1,TPO,GN,GN,GN,GN,GN,GN,GN,GN
14    FORMAT(' * 11',I5,5X,' * 12',F9.3,' * 13',F9.3,' * 14',F9.3,
     1' * 15',F9.3,' *'/' * 16',F9.3,' * 17',F9.3,' * 18',F9.3,' * 19'
     2,F9.3,' * 20',F9.3,' *')
      WRITE(J,20)LAPH,WAPH,NAPH,TMAPH,TAPH,RAF,DOH,DIH,LHH,NTH
20    FORMAT(' * ENGINE DIMENSIONS',9X,'*',13X,'*',13X,'*',13X,'*'/
     1' * 21',F9.3,' * 22',F9.3,' * 23',I5,5X,' * 24',F9.3,' * 25',F9.3,
     2' *'/' * 26',F9.3,' * 27',F9.3,' * 28',F9.3,' * 29',F9.3,' * 30',
     3I5,5X,' *')
      WRITE(J,22)LR,FF,NS,MSH,GN,GN,GN,GN,GN,GN
22    FORMAT(' * 31',F9.3,' * 32',F9.3,' * 33',I5,5X,' * 34',F9.3,
     1' * 35',F9.3,' *'/' * 36',F9.3,' * 37',F9.3,' * 38',F9.3,' * 39',
     2F9.3,' * 40',F9.3,' *')
      WRITE(J,28)
28    FORMAT(' ',71('*')/' II XXXXXXXXXX',12X,'TYPE 48 TO END',5X,
     1'TYPE 49 TO EXECUTE NEW CASE')
      READ(5,36)J7,QQ
36    FORMAT(I2,2X,F10.2)
      IF(J7-9)45,45,38
38    IF(J7-19)47,47,39
39    IF(J7-29)49,49,40
40    IF(J7-39)50,50,51
45    GO TO (53,54,55,56,57,58,59,60,61),J7
47    J7=J7-9
      GO TO (62,63,64,65,66,67,68,69,70,71),J7
49    J7=J7-19
      GO TO (72,73,74,75,76,77,78,79,80,81),J7
50    J7=J7-29
```

```
      GO TO (82,83,84,85,86,87,88,89,90,91),J7
51    J7=J7-39
      GO TO (92,93,94,95,96,97,98,99,100,101),J7
53    THMG=QQ
      GOTO9
54    TPB=QQ
      GOTO9
55    T1=QQ
      GOTO9
56    DT=QQ
      GOTO9
57    FFF=QQ
      GOTO9
58    THU=QQ
      GOTO9
59    NO=QQ
      GOTO9
60    HREQ=QQ
      GOTO9
61    TTT=QQ
      GOTO9
62    TOTT=QQ
      GOTO9
63    Q1=QQ
      GOTO9
64    TPO=QQ
      GOTO9
65    GN=QQ
      GOTO9
66    GN=QQ
      GOTO9
67    GN=QQ
      GOTO9
68    GN=QQ
      GOTO9
69    GN=QQ
      GOTO9
70    GN=QQ
      GOTO9
71    GN=QQ
      GOTO9
72    GN=QQ
      GOTO9
73    LAPH=QQ
      GOTO9
74    WAPH=QQ
      GOTO9
75    NAPH=QQ
      GOTO9
76    TMAPH=QQ
      GOTO9
77    TAPH=QQ
      GOTO9
```

```
78      RAF=QQ
        GOTO9
79      DOH=QQ
        GOTO9
80      DIH=QQ
        GOTO9
81      LHH=QQ
        GOTO9
82      NTH=QQ
        GOTO9
83      LR=QQ
        GOTO9
84      FF=QQ
        GOTO9
85      NS=QQ
        GOTO9
86      MSH=QQ
        GOTO9
87      GN=QQ
        GOTO9
88      GN=QQ
        GOTO9
89      GN=QQ
        GOTO9
90      GN=QQ
        GOTO9
91      GN=QQ
        GOTO9
92      GN=QQ
        GOTO9
93      GN=QQ
        GOTO9
94      GN=QQ
        GOTO9
95      GN=QQ
        GOTO9
96      GN=QQ
        GOTO9
97      GN=QQ
        GOTO9
98      GN=QQ
        GOTO9
99      GN=QQ
        GOTO9
100     GOTO5000
101     CONTINUE
        IF(Q1.GE.1)WRITE(2,195)
195     FORMAT('  TIME(SEC)     HT TUBE (K)  FUEL FLOW(G/S)  HEAT REQ(W)
     1 '    BURNER EFF%  APH MET NODE  APH HT BAL% '/)
C   ********* BURNER INITIALIZATION *********
        DO 200 I=1,NO
200     EX(I)=T1
C   HEAT CAPACITY OF AIR PREHEATER METAL ASSUMING STEEL WITH
```

```
C    5.00 J/CU CM K HEAT CAPACITY
         CMAPH=LAPH*WAPH*2.*NAPH*TMAPH*2.5
C    FLOW AREA IN PREHEATER
         AFAPH=WAPH*TAPH*NAPH
C    HEAT TRANSFER CONSTANTS
         RA1=RAF+1
         CZ=CPFG*RA1
         DEQ=2.*WAPH*TAPH/(WAPH+TAPH)
         UXY=LAPH*WAPH*2.*NAPH/(NO*CZ)
         DT2=LHV/CZ
         CY=CPA*RAF*NO/CMAPH
         UXX=LAPH*WAPH*2.*NAPH/(NO*RAF*CPA)
         CYY=CZ*NO/CMAPH
         FUEL=0.
C    MINIMUM FLOW AREA FOR FLUE GAS THROUGH GAS HEATER
         AMF=DOH*LHH*NTH*2.
C  HEAT TRANSFER AREA TO PLANE FOR COMPLETE ENGINE
         AH=AMF*2*PI
C  HEAT CAPACITY OF GAS HEATER FOR ONE CYLINDER
         CMH=4.71*PI4*(DOH**2-DIH**2)*LHH*NTH
C    INITIALIZE CUMULATIVE HEAT INPUT
         DO 198 I=1,4
         THM(I)=T1
198      UHI(I)=0
         QEX=0
         TT=0
         TIM=0
         CALL CLEAR
         I1=512
         I2=1023
         J1=390
         J2=390
         CALL VECTOR(I1,J1,I2,J2)
         J1=0
         J2=0
         CALL VECTOR(I1,J1,I2,J2)
         I1=1023
         J1=779
         CALL VECTOR(I2,J2,I1,J1)
         I2=512
         J2=779
         CALL VECTOR(I1,J1,I2,J2)
         I1=512
         J1=0
         CALL VECTOR(I2,J2,I1,J1)
         J1=380
         J2=400
         DO 390 I=1,11
         I1=45*(I-1)+543
         I2=I1
390      CALL VECTOR(I1,J1,I2,J2)
         NO2=NO/2
```

```
      TIN(1)=T1
C ********* GAS HEATER WARM UP *********
  400 TIM=TIM+DT
      TA=(THM(1)+THM(2)+THM(3)+THM(4))/4
C   TEMPERATURE ERROR (FOR CONTROL)
      TE=THMG-TA
C   CURRENT FUEL FLOW
      IF(TE)405,405,406
  405 CFF=0.01*FFF
      GOTO409
  406 IF(TE-TPB)408,407,407
  407 CFF=FFF
      GOTO409
  408 CFF=FFF*(TE)/TPB
  409 CONTINUE
      FUEL=FUEL+CFF*DT
C  HEAT TRANSFER CALCULATIONS
C   AIR TEMPERATURES
C    HEAT TRANSFER COEFFICIENT
      GAPH=CFF*RAF/AFAPH
      RE=DEQ*GAPH*2500.
      CALL STANTN(RE,STN)
      X=UXX*STN*GAPH*1.19/CFF
      IF(32.-X)420,420,425
  420 DO 422 I=1,NO
  422 TIN(I+1)=EX(I)
      GO TO 428
  425 X=EXP(X)
      DO 427 I=1,NO
  427 TIN(I+1)=EX(I)-(EX(I)-TIN(I))/X
  428 CONTINUE
C  ADJUST HEAT EXCHANGER METAL TEMPERATURES
      X=CY*CFF*DT
      DO 430 I=1,NO
  430 EX(I)=EX(I)-X*(TIN(I+1)-TIN(I))
      FLAME=TIN(NO+1)+DT2
C  HEAT FLUX TO ALL HEATERS
C  OUTSIDE CONTROLLING HEAT TRANSFER COEFFICIENT
      UH=(DOH*CFF*RA1/AMF/.0006)**0.5*.0003/DOH
  433 X=UH*AH/(CZ*32.)
      DO 438 I=1,4
      IF(CFF-X)435,435,437
  435 T3A(I)=THM(I)
      GOTO438
  437 T3A(I)=THM(I)+(FLAME-THM(I))/EXP(X*32./CFF)
  438 CONTINUE
      TOU(NO+1)=(T3A(1)+T3A(2)+T3A(3)+T3A(4))/4.
C  EXIT FLUE GAS TEMPCRATURES THROUGH AIR PREHEATER
C   HEAT TRANSFER COEFFICIENT, FLUE GAS SIDE
      GAPH=CFF*(RA1)/AFAPH
      RE=DEQ*GAPH*2500
      CALL STANTN(RE,STN)
      X=STN*GAPH*1.19*UXY/CFF
      IF(X-32.)444,440,440
```

```
440     DO 442 I=1,NO
442     TOU(I)=EX(I)
        GOTO448
444     X=EXP(X)
        DO446 I=1,NO
        J=NO-I+1
446     TOU(J)=EX(J)-(EX(J)-TOU(J+1))/X
C  READJUST AIR PREHEATER METAL TEMPERATURE
448     X=CYY*CFF*DT
        DO 450 I=1,NO
450     EX(I)=EX(I)+X*(TOU(I+1)-TOU(I))
C  TEMPERATURE EQUILIBRATION FOR TIME STEP WITH NO VOLUME CHANGE
C  --TO SHORTEN CALCULATION IT IS ASSUMED THAT HEAT TRANSFER IN THE
C     HOT AND COLD SPACES IS NON-EXISTANT AND THE HEAT TRANSFER
C     IN THE OTHER SPACES IS PERFECT
C  IN GAS HEATERS
C   BURNER HEATING
        DO 489 I=1,4
        QE=DT*C2*CFF*(FLAME-TGA(I))/4.
        IF(JA.LT.2)GOTO489
C   CUMMULATIVE HEAT INPUT FOR CYCLE
        QHI(I)=QHI(I)+QEX
C   CHANGE IN TEMPERATURE OF HEATER METAL
489     THM(I)=THM(I)+(QE-QEX)/CMH
        BEF=QEX/DT/(CFF*LHV)*400
        I1=TIM/TOTT*450+543
        J1= 20*(TA-300. )+410
        CALL POINT(I1,J1)
        J1= 20*(EX(NO)-300)+410
        CALL POINT(I1,J1)
        J1= 20*(EX(1)-300. )+410
        CALL POINT(I1,J1)
        J1=CFF/FFX*250+20
        CALL POINT(I1,J1)
        J1=BEF*3.5+20
        CALL POINT(I1,J1)
        IF(TIM-TT)520,505,505
505     TT=TT+TPO
        HTA=CPA*RAF*(TIN(NO+1)-TIN(1))
        HTF=CPFG*RA1*(TOU(NO+1)-TOU(1))
        IF(HTA.LT.99.)GOTO510
        BAL=(HTA-HTF)/HTA*100.
        GOTO512
510     BAL=100.
512     WRITE(5,517)TIN(1),TIN(NO+1),EX(1),EX(NO2),EX(NO),FLAME,
     1  TOU(1),TOU(NO+1)
517     FORMAT(//' ',F6.0,1X,20('*'),F7.0/8X,'*',18X,'*'/8X,'*',
     1  F4.0,F7.0,'*',F12.0/8X,'*',18X,'*'/' ',F6.0,1X,20('*'),F7.0)
        WRITE(5,518)BEF,BAL,CFF
518     FORMAT(/' BURN EFF',F5.1,' APH BAL',F6.1,' CFF',F7.3)
        X=QEX/DT
        IF(Q1.GE.1)WRITE(2,519)TIM,TA,CFF,X,BEF,EX(NO),BAL
```

```
519     FORMAT(' ',F8.2,F17.4,F14.4,4F14.4)
520     IF(TIM-THU)400,400,540
540     QEX=QEX+HREQ*DT/4.
        IF(TIM.GT.TOTT)GOTO600
        THU=THU+TTT
        GOTO400
600     READ(5,610)X
610     FORMAT(F10.2)
        GOTO9
5000    STOP
        END

        SUBROUTINE STANTN(RE,STN)
        IF(RE-2000.)100,100,200
100     STN=EXP(1.6908-.9363*ALOG(RE))
        GOTO300
200     STN=EXP(-4.0555-.1803*ALOG(RE))
300     RETURN
        END
```

APPENDIX B

SHAFT TORQUE CORRELATION

The shaft torque is lower than the indicated torque due to two friction losses; mechanical friction and flow losses inside the engine. Flow losses can be calculated using fluid mechanics principles, but for the sake of simplicity, it was desired to derive a correlation that would approximate engine flow loss at various speeds and working gas pressures.

ISO.FOR is a computer code developed by Martini Engineering (6) that calculates flow losses in the heater, regenerator and cooler of the 4L23 engine using fluid mechanics principles. The program was executed 16 times, with four pressures ranging from 1.38-9.66 MPa and four speeds ranging from 3.33 to 33.3 Hz. The ratios of net torque (indicated less the flow losses) to indicated torque were plotted for the 16 cases and are shown in Figure B.1. The full input and output of these cases are given in Table B.1.

It was noted that the flow losses increased with speed and decreased with pressure. The effect of pressure on the flow loss increases with speed. It was decided to use these two relationships to determine the flow loss correlation.

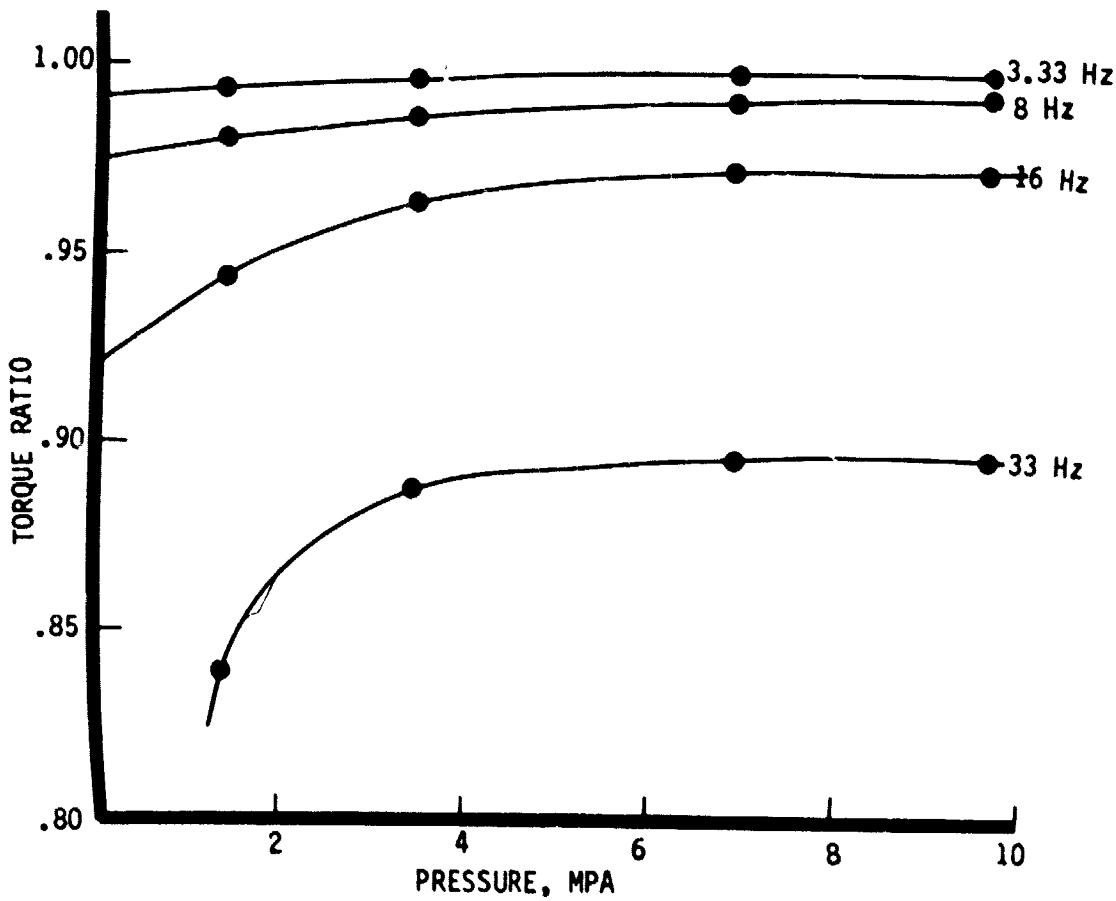

Figure B.1. Torque Ratio for Various Pressures and Speeds.

Table B.1

FULL INPUTS AND OUTPUTS FOR 16 CASES
USED TO DERIVE TORQUE CORRELATION

Nomenclature

Symbol	Meaning and units
SP	Engine Speed, rpm
PS	Average Pressure, psia
ND	Number of degrees in angle increment
TF	Inside Heater Tube Wall Temperature, F
L1	Fraction of Total Gas Charge Leakage per MPaΔP per second
TY	Inlet Cooling Water Temperature, F
FX	Cooling Water Flow gpm @ 2000 rpm per cylinder
OG	Operating Gas, 1 = hydrogen, 2 = helium, 3 = air
DC	Diameter of engine cylinder, cm
DR	Diameter of regenerator, cm
IC	ID of cooler tubes, cm
OC	OD of cooler tubes, cm
DW	Diameter of "wire" in regenerators
DD	Diameter of piston Drive Rod, cm
IH	ID of Heater Tubes, cm
OH	Heater Tube OD, cm
G	Gap in hot cap, cm = 0.56 cm
LB	Length of Hot Cap, cm
LR	Length of Regenerator, cm
CR	Length of Connecting Rod, cm
RC	Crank Radius, cm
LC	Length of cooler Tube, cm
LD	Heat Transfer Length of Cooler Tube, cm
LH	Heater Tube Length, cm
LI	Heater Tube Heat Transfer Length, cm
NC	Number of Cooler Tubes per Cylinder
NR	Number of Regenerators per cylinder
N	Number of Cylinders per Engine
NH	Number of Heater Tubes per Cylinder

Table B.1 (continued)

Symbol	Meaning and units
FF	Filler factor, fraction of regenerator volume filled with solid
AL	Phase Angle Alpha = 90 degrees
CX	Cold dead volume outside cooler Tubes, cm^3 (determined by other input only)
ME	Mechanical Efficiency, %
FE	Furnace Efficiency, %
EC	Piston End Clearance, cm
SC	Wall Thickness of Hot Cap, cm
SE	Wall Thickness of Expansion Cylinder Wall, cm
SR	Wall Thickness of Regenerator Housing,cm
ZZ	0 for Specified Static Conduction, 1 for Calculated Static Conduction
ZH	Specified Static Heat Conduction Loss, watts
KM	Metal Thermal Conductivity, w/cm K
ID	Inside Diameter of Connecting Duct, cm
LE	Length of Connecting Duct, cm
NE	Number of Connecting Ducts per Cylinder
BF	Bugger Factor to Convert Power Outputs to Nearly What GM Says They Should Be

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    200.00   PS=    200.00   ND=     30.00   TF=   1200.00
L1=    0.0000   TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=     .1150   OC=     .1670
DW=    .00432   DD=    4.0600   IH=     .4720   OH=     .6400
G=     .04060   LB=    6.4000   LR=    2.5000   CR=   13.6500
RC=    2.3250   LC=   12.9000   LD=   12.0200   LH=   41.8000
LI=   25.5800   NC=  312        NR=  6          N=   4
NH=  36         FF=     .2000   AL=     90.00   CX=  254.2804
ME=   90.0000   FE=   80.0000   EC=    .04060   SC=    .06350
SE=    .10160   SR=    .05100   ZZ=  1          ZH=    216.37
KM=     .2000   ID=     .7600   LE=   71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                         HEAT REQUIREMENT, WATTS
  BASIC                 1469.2197      BASIC                 2438.5757
  HEATER F.L.               .9384      REHEAT                  47.4414
  REGEN.F.L.               7.4303      SHUTTLE               2056.8794
  COOLER F.L.               .8388      PUMPING                  1.2134
  NET                   1460.0123      TEMP.SWING              41.6411
  MECH.FRIC.             146.0013      CONDUCTION             216.3688
  BRAKE                 1314.0111      FLOW FRIC.CREDIT        -4.6535
---------------------------------- HEAT TO ENGINE         4797.4658
INDICATED EFF.%=   30.4330           FURNACE LOSS          1199.3665
OVERALL EFF.%=   21.9117             FUEL INPUT            5996.8320
-----------------------------------------------------
HOT METAL TEMP. K=  922.2222      COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  876.3427    EFFEC.COLD SP.TEMP.K =  348.5838
-----------------------------------------------------
```

Table B.1 (continued)

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    200.00   PS=    500.00   ND=     30.00   TF=  1200.00
L1=    0.0000   TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=     .1150   OC=     .1670
DW=    .00432   DD=    4.0600   IH=     .4720   OH=     .6400
G=     .04060   LB=    6.4000   LR=    2.5000   CR=  13.6500
RC=    2.3250   LC=   12.9000   LD=   12.0200   LH=  41.8000
LI=   25.5800   NC=  312        NR=  6          N=   4
NH=  36         FF=     .2000   AL=     90.00   CX=  254.2804
ME=   90.0000   FE=   80.0000   EC=    .04060   SC=    .06350
SE=    .10160   SR=    .05100   ZZ=  1          ZH=    205.01
KM=     .2000   ID=     .7600   LE=   71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                      HEAT REQUIREMENT, WATTS
  BASIC               3530.6177    BASIC                  6026.9458
  HEATER F.L.            1.3490    REHEAT                  120.7603
  REGEN. F.L.            8.3425    SHUTTLE                1948.9211
  COOLER F.L.            1.3411    PUMPING                   5.1704
  NET                 3519.5852    TEMP. SWING             252.7231
  MECH. FRIC.          351.9586    CONDUCTION              205.0124
  BRAKE               3167.6267    FLOW FRIC. CREDIT        -5.5202
---------------------------------- HEAT TO ENGINE         8554.0117
INDICATED EFF.%=    41.1454        FURNACE LOSS           2138.5029
OVERALL EFF.%=    29.6247          FUEL INPUT            10692.5137
----------------------------------------------------------
HOT METAL TEMP. K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC HOT SP TEMP K=  853.7064   EFFEC COLD SP TEMP K =  353.9690
----------------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=     200.00   PS=    1000.00   ND=      30.00   TF=   1200.00
L1=     0.0000   TY=  135.0000    FX=    25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600    DR=     3.5000   IC=      .1150   OC=       .1670
DW=     .00432   DD=     4.0600   IH=      .4720   OH=       6400
[illegible]      .04060  LB=     6.4000   LR=     2.5000   CR=    13.6500
RC=    2.3250    LC=    12.9000   LD=    12.0200   LH=    41.8000
LI=   25.5800    NC=  312         NR=  6           N=    4
NH=  36          FF=      .2000   AL=      90.00   CX=   254.2804
ME=   90.0000    FE=    80.0000   EC=      .04060  SC=      .06350
SE=     .10160   SR=     .05100   ZZ=  1           ZH=     185.61
KM=      .2000   ID=      .7600   LE=    71.0000   NE=   6
BF=      .4000   BB=
POWER, WATTS                     HEAT REQUIREMENT, WATTS
  BASIC                6518.2021   BASIC                  11768.6221
  HEATER F.L.             2.3809   REHEAT                   235.2546
  REGEN. F.L.             9.8929   SHUTTLE                 1764.4348
  COOLER F.L.             2.4394   PUMPING                   15.1419
  NET                  6503.4893   TEMP. SWING              950.1328
  MECH. FRIC.           650.3491   CONDUCTION               185.6057
  BRAKE                5853.1406   FLOW FRIC. CREDIT         -7.3273
---------------------------------- HEAT TO ENGINE         14911.8633
INDICATED EFF.%=    43.6128        FURNACE LOSS            3727.9658
OVERALL EFF.%=    31.4013          FUEL INPUT             18639.8281
-----------------------------------------------------
HOT METAL TEMP. K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  818.2180   EFFEC.COLD SP.TEMP.K. =  364.9307
-----------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=     200.00   PS=   1400.00   ND=      30.00   TF=   1200.00
L1=     0.0000   TY=  135.0000   FX=    25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=    10.1600   DR=     3.5000   IC=      .1150   OC=      .1670
DW=     .00432   DD=     4.0600   IH=      .4720   OH=      .6400
G=      .04060   LB=     6.4000   LR=     2.5000   CR=    13.6500
RC=     2.3250   LC=    12.9000   LD=    12.0200   LH=    41.8000
LI=    25.5800   NC=  312         NR=  6           N=   4
NH=  36          FF=      .2000   AL=      90.00   CX=   254.2804
ME=    90.0000   FE=    80.0000   EC=     .04060   SC=     .06350
SE=     .10160   SR=     .05100   ZZ=  1           ZH=     176.30
KM=      .2000   ID=      .7600   LE=    71.0000   NE=  6
BF=      .4000   BB=
POWER, WATTS                        HEAT REQUIREMENT, WATTS
  BASIC                 8790.2656   BASIC                  16311.7012
  HEATER F.L.              3.3721   REHEAT                   324.3701
  REGEN F.L.              11.2076   SHUTTLE                 1676.0105
  COOLER F.L.              3.3873   PUMPING                   25.4798
  NET                   8772.2988   TEMP.SWING              1808.3601
  MECH.FRIC.             877.2300   CONDUCTION               176.3041
  BRAKE                 7895.0693   FLOW FRIC.CREDIT          -8.9759
----------------------------------- HEAT TO ENGINE         20313.2480
INDICATED EFF %=   43.1851          FURNACE LOSS            5078.3115
OVERALL EFF.%=   31.0933            FUEL INPUT             25391.5586
----------------------------------------------------
HOT METAL TEMP.  K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  798.3881   EFFEC.COLD SP.TEMP.K =  368.2829
----------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    500.00   PS=    200.00   ND=     30.00   TF=   1200.00
L1=    0.0000   TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=     .1150   OC=     .1670
DW=    .00432   DD=    4.0600   IH=     .4720   OH=     .6400
G=     .04060   LB=    6.4000   LR=    2.5000   CR=   13.6500
RC=    2.3250   LC=   12.9000   LD=   12.0200   LH=   41.8000
LI=   25.5800   NC=  312        NR=  6          N=   4
NH=  36         FF=     .2000   AL=     90.00   CX=  254.2804
ME=   90.0000   FE=   80.0000   EC=    .04060   SC=    .06350
SE=    .10160   SR=    .05100   ZZ=  1          ZH=    205.71
KM=     .2000   ID=     .7600   LE=   71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                      HEAT REQUIREMENT, WATTS
  BASIC                 3541.0508   BASIC                 6032.8877
  HEATER F.L.              8.4157   REHEAT                 121.0556
  REGEN F.L.              52.0297   SHUTTLE               1955.5525
  COOLER F.L.              8.3694   PUMPING                  5.1772
  NET                   3472.2361   TEMP SWING             101.3289
  MECH FRIC              347.2237   CONDUCTION             205.7099
  BRAKE                 3125.0125   FLOW FRIC CREDIT       -34.4306
-----------------------------------  HEAT TO ENGINE        8387.2803
INDICATED EFF %=   41.3988          FURNACE LOSS          2096.8198
OVERALL EFF %=   29.8072            FUEL INPUT           10484.0996
---------------------------------------------------
HOT METAL TEMP  K=  922.2222     COOLING WATER INLET TEMP , K=  330.5555
EFFEC HOT SP TEMP k=  854.9666   EFFEC COLD SP TEMP k =  353.4785
---------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    500.00   PS=    500.00   ND=     30.00   TF=   1200.00
L1=    0.0000   TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=     .1150   OC=      .1670
DW=    .00432   DD=    4.0600   IH=     .4720   OH=      .6400
G=     .04060   LB=    6.4000   LR=    2.5000   CR=    13.6500
RC=    2.3250   LC=   12.9000   LD=   12.0200   LH=    41.0000
LI=   25.5000   NC=  312        NR=  6          N=   4
NH=  36         FF=     .2000   AL=     90.00   CX=   254.2004
ME=   90.0000   FE=   80.0000   EC=    .04060   SC=     .06350
SE=    .10160   SR=    .05100   ZZ=  1          ZH=     180.37
KM=     .2000   ID=     .7600   LE=   71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                      HEAT REQUIREMENT, WATTS
  BASIC                 7999.3301   BASIC                  14640.6025
  HEATER F.L.             18.7768   REHEAT                   292.0714
  REGEN. F.L.             66.9300   SHUTTLE                 1714.6409
  COOLER F.L.             18.9975   PUMPING                   21.4229
  NET                   7894.6260   TEMP. SWING              504.8383
  MECH. FRIC.            789.4628   CONDUCTION               180.3678
  BRAKE                 7105.1636   FLOW FRIC. CREDIT        -52.2418
----------------------------------  HEAT TO ENGINE         17381.7012
INDICATED EFF.%=   45.4192          FURNACE LOSS            4345.4243
OVERALL EFF.%=   32.7018            FUEL INPUT             21727.1250
--------------------------------------------------------
HOT METAL TEMP. K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC. HOT SP. TEMP. K=  806.0847   EFFEC. COLD SP. TEMP. K =  365.5099
--------------------------------------------------------
```

Table B.1 (continued)

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    500.00   PS=   1000.00   ND=     30.00   TF=   1200.00
L1=    0.0000   TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=     .1150   OC=      .1670
DW=    .00432   DD=    4.0600   IH=     .4720   OH=      .6400
G=     .04060   LB=    6.4000   LR=    2.5000   CR=    13.6500
RC=    2.3250   LC=   12.9000   LD=   12.0200   LH=    41.8000
LI=   25.5800   NC=  312        NR=  6          N=    4
NH=  36         FF=     .2000   AL=     90.00   CX=   254.2804
ME=   90.0000   FE=   80.0000   EC=    .04060   SC=     .06350
SE=    .10160   SR=    .05100   ZZ=  1          ZH=     195.95
KM=     .2000   ID=     .7600   LE=   71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                     HEAT REQUIREMENT, WATTS
  BASIC              17191.9375    BASIC                  29910.8047
  HEATER F.L.           34.2715    REHEAT                   641.8933
  REGEN. F.L.           85.3313    SHUTTLE                 1862.7869
  COOLER F.L.           34.9928    PUMPING                   66.6066
  NET                17037.3437    TEMP. SWING             2475.5483
  MECH. FRIC.         1703.7346    CONDUCTION               195.9516
  BRAKE              15333.6094    FLOW FRIC. CREDIT        -76.9372
---------------------------------  HEAT TO ENGINE         35076.6523
INDICATED EFF.%=    48.5717        FURNACE LOSS            8769.1621
OVERALL EFF.%=    34.9717          FUEL INPUT             43845.8125
------------------------------------------------------
HOT METAL TEMP. K=  922.2222    COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  832.8246   EFFEC.COLD SP.TEMP.K =  353.8192
------------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    500.00   PS=   1400.00   ND=      30.00   TF=   1200.00
L1=    0.0000   TY=  135.6000   FX=    25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   19.1600   DR=    3.5000   IC=      .1150   OC=      .1670
DW=    .00432   DD=    4.0600   IH=      .4720   OH=      .6400
G=     .04060   LB=    6.4000   LR=     2.5000   CR=    13.6500
RC=    2.3250   LC=   12.9000   LD=    12.0200   LH=    41.8000
L1=   25.5800   NC=  312        NR=  6           N=   4
NH=  36         FF=     .2000   AL=      90.00   CX=   254.2804
ME=   90.0000   FE=   80.0000   EC=     .04060   SC=     .06350
SE=    .10160   SR=    .05100   ZZ=  1           ZH=     201.08
KM=     .2000   ID=     .7600   LE=    71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                        HEAT REQUIREMENT, WATTS
  BASIC                 24448.1367    BASIC                  42064.4766
  HEATER F.L.              45.4336    REHEAT                   933.3535
  REGEN. F.L.              98.8550    SHUTTLE                 1911.5562
  COOLER F.L.              46.5041    PUMPING                  114.9268
  NET                   24257.3457    TEMP. SWING             4924.7031
  MECH. FRIC.            2425.7351    CONDUCTION               201.0818
  BRAKE                 21831.6113    FLOW FRIC. CREDIT        -94.8611
----------------------------------- HEAT TO ENGINE           50055.2305
INDICATED EFF.%=   48.4612            FURNACE LOSS           12513.8066
OVERALL EFF.%=   34.8920              FUEL INPUT             62569.0312
----------------------------------------------------------
HOT METAL TEMP. K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP. TEMP.K=  844.6619   EFFEC.COLD SP.TEMP.K. =  353.6819
----------------------------------------------------------
```

Table B.1 (continued)

<u>Input and Output Printouts</u>

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=   1000.00   [illegible]    200.00   ND=     30.00   TF=   1200.00
L1=    0.0000   TY=  135.0000   FX=    25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=      .1150   OC=      .1670
DW=    .00432   DD=    4.0600   IH=      .4720   OH=      .6400
G=     .04060   LB=    6.40[illegible]   LR=     2.5000   CR=   13.6500
RC=    2.3250   LC=   12.9[illegible]   LD=    12.0200   LH=   41.8000
LI=   25.5800   NC=  312        NR=  6            N=    4
NH=  36         FF=     .2000   AL=      90.00   CX=  254.2804
ME=   90.0000   FE=   80.0000   EC=     .04050   SC=     .06350
SE=    .10160   SR=    .05100   ZZ=  1            ZH=    188.67
KM=     .2000   ID=     .7600   LE=    71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                        HEAT REQUIREMENT, WATTS
  BASIC                 6609.6807     BASIC                11817.2197
  HEATER F.L.             59.0550     REHEAT                 237.8720
  REGEN. F.L.            245.4482     SHUTTLE               1793.6062
  COOLER F.L.             60.7231     PUMPING                 15.2238
  NET                   6244.4546     TEMP. SWING            192.0667
  MECH. FRIC.            624.4456     CONDUCTION             188.6743
  BRAKE                 5620.0093     FLOW FRIC. CREDIT     -181.7791
-------------------------------------  HEAT TO ENGINE       14062.8877
INDICATED EFF.%=   44.4038            FURNACE LOSS          3515.7217
OVERALL EFF.%=   31.9707              FUEL INPUT           17578.6094
-------------------------------------------------------
HOT METAL TEMP. K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC. HOT SP. TEMP. K=  823.8007    EFFEC. COLD SP. TEMP. K =  362.7874
-------------------------------------------------------
```

Table B.1 (continued)

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=   1000.00   PS=    500.00   ND=     30.00   TF=   1200.00
L1=     0.0000  TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=    3.5000   IC=     .1150   OC=     .1670
DW=    .00432   DD=    4.0600   IH=     .4720   OH=     .6400
G=     .04060   LR=    6.4000   LR=    2.5000   CR=   13.6500
RC=    2.3250   LC=   12.9000   LD=   12.0200   LH=   41.8000
LI=   25.5800   NC=  312        NR=  6          N=   4
NH=  36         FF=     .2000   AL=     90.00   CX=  254.2804
ME=   90.0000   FE=   80.0000   EC=    .04060   SC=    .06350
SE=    .10160   SR=    .05160   ZZ=  1          ZH=    197.90
KM=     .2000   ID=     .7600   LE=   71.8000   NE=  6
BF=     .4000   BB=
POWER, WATTS                           HEAT REQUIREMENT, WATTS
  BASIC                 17336.1367     BASIC                 29987.6992
  HEATER F.L.             136.4090     REHEAT                  646.2640
  REGEN F.L.              339.8281     SHUTTLE                1881.3140
  COOLER F.L.             139.5549     PUMPING                  66.8533
  NET                   16720.3457     TEMP. SWING            1245.6926
  MECH FRIC              1672.0349     CONDUCTION              197.9006
  BRAKE                 15048.3125     FLOW FRIC CREDIT       -306.3230
---------------------------------- HEAT TO ENGINE         33719.3984
INDICATED EFF %=   49.5867             FURNACE LOSS           8429.8496
OVERALL EFF %=   35.7024               FUEL INPUT            42149.2422
----------------------------------------------------
HOT METAL TEMP K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC HOT SP TEMP K=  836.1503   EFFEC COLD SP TEMP K =  352.5077
----------------------------------------------------
```

Table B.1 (continued)

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=    1000.00    PS=    1000.00    ND=      30.00    TF=    1200.00
L1=     0.0000    TY=   135.0000    FX=    25.0000    OG= 1


CURRENT DIMENSIONS ARE:
DC=    10.160[illegible]  DR=     3.5000    IC=      .1150    OC=       .1670
DW=     .00432    DD=     4.0600    IH=      .4720    OH=       .6400
G=      .04060    LB=     6.4000    LR=     2.5000    CR=     13.6500
RC=     2.3250    LC=    12.9000    LD=    12.0200    LH=     41.8000
LI=    25.5800    NC=   312         NR=   6           N=    4
NH=   36          FF=      .2000    AL=      90.00    CX=    254.2804
ME=    90.0000    FC=    8[illegible].000[illegible]    EC=     .04060    SC=      .06350
SE=     .10160    S[illegible]=     .05100    ZZ=   1           ZH=     201.67
KM=      .2000    ID=      .76[illegible]    LE=    71.0000    NE=   6
BF=      .4000    B[illegible]=
POWER, WATTS                        HEAT REQUIREMENT, WATTS
  BASIC               34[illegible]54.0937    BASIC                  60104.5156
  HEATER F.L.           251.3977    REHEAT                  1364.5796
  REGEN. F.L.           484.0062    SHUTTLE                 1917.1147
  COOLER F.L.           256.2751    PUMPING                  203.1112
  NET                 33962.4180    TEMP. SWING             5037.6309
  MECH. FRIC.          3396.2422    CONDUCTION               201.6665
  BRAKE               30566.1758    FLOW FRIC. CREDIT       -493.4[illegible]8
----------------------------------  HEAT TO ENGINE         68335.2187
INDICATED EFF.%=   49.6997          FURNACE LOSS           17083.8047
OVERALL EFF.%=   35.7838            FUEL INPUT             85419.0078
-----------------------------------------------------
HOT METAL TEMP. K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC. HOT SP. TEMP. K=  845.7805   EFFEC. COLD SP. TEMP. K. =  354.2686
-----------------------------------------------------
```

Table B.1 (continued)

Inputs and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=   1000.00   PS=   1400.00   ND=      30.00   TF=   1200.00
L1=     0.0000  TY=  135.0000   FX=    25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=    10.1600  DR=     3.5000  IC=      .1150   OC=      .1670
DW=     .00432  DD=     4.0600  IH=      .4720   OH=      .6400
G=      .04060  LB=     6.4000  LR=     2.5000   CR=    13.6500
RC=     2.3250  LC=    12.9000  LD=    12.0200   LH=    41.8000
LI=    25.5800  NC=  312        NR=  6           N=   4
NH=  36         FF=      .2000  AL=      90.00   CX=   254.2804
ME=    90.0000  FE=    80.0000  EC=     .04060   SC=     .06350
SE=     .10160  SR=     .05100  ZZ=  1           ZH=     197.29
KM=       200.  ID=      .7600  LE=    71.0000   NE=  6
BF=      .4000  BB=
POWER, WATTS                         HEAT REQUIREMENT, WATTS
  BASIC                 47958.7500   BASIC                   83615.6094
  HEATER F.L.             345.9294   REHEAT                   1920.1501
  REGEN.F.L.              607.2909   SHUTTLE                  1875.4663
  COOLER F.L.             350.3559   PUMPING                   343.8532
  NET                   46655.1758   TEMP.SWING               9749.3984
  MECH.FRIC.             4665.5186   CONDUCTION                197.2854
  BRAKE                 41989.6602   FLOW FRIC.CREDIT         -649.5749
------------------------------------ HEAT TO ENGINE          97052.1875
INDICATED EFF.%=   48.0723           FURNACE LOSS            24263.0469
OVERALL EFF.%=   34.6120             FUEL INPUT             121315.2187
------------------------------------------------------------
HOT METAL TEMP. K=  922.2222      COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  838.6689    EFFEC.COLD SP.TEMP.K =  358.1397
------------------------------------------------------------
```

Table B.1 (continued)

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=  2000.00   PS=    200.00   ND=     30.00   TF=   1200.00
L1=    0.0000  TY=  135.0000   FX=    25.0000  OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600  DR=     3.5000  IC=      .1150  OC=      .1670
DW=    .00432  DD=     4.0600  IH=      .4720  OH=      .6400
G=     .04060  LB=     6.4000  LR=     2.5000  CR=   13.6500
RC=    2.2250  LC=    12.9000  LD=    12.0200  LH=   41.8000
LI=   25.5800  NC=   312       NR=   6         N=    4
NH=  36        FF=      .2000  AL=      90.00  CX=  254.2804
ME=   90.0000  FE=    80.0000  EC=     .04060  SC=     .06350
SE=    .10160  SR=     .05100  ZZ=   1         ZH=    191.16
KM=     .2000  ID=      .7600  LE=    71.0000  NE=   6
BF=     .4000  BB=
POWER, WATTS                     HEAT REQUIREMENT, WATTS
  BASIC               13460.6621   BASIC                  23766.1650
  HEATER F.L.           451.0111   REHEAT                   498.5541
  REGEN.F.L.           1244.0168   SHUTTLE                 1817.2532
  COOLER F.L.           458.8881   PUMPING                   46.2341
  NET                 11306.7461   TEMP.SWING               389.0685
  MECH.FRIC.           1130.6748   CONDUCTION               191.1619
  BRAKE               10176.0713   FLOW FRIC.CREDIT       -1073.0195
---------------------------------- HEAT TO ENGINE         25635.4160
INDICATED EFF.%=   44.1059         FURNACE LOSS            6408.8535
OVERALL EFF.%=   31.7563           FUEL INPUT             32044.2656
---------------------------------------------------------
HOT METAL TEMP. K=  922.2222    COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  824.1782   EFFEC.COLD SP TEMP.K =  357.3217
---------------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITIEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=   2000.00   PS=     500.00   ND=      30.00   TF=   1200.00
L1=     0.0000  TY=   135.0000   FX=     25.0000  OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1600   DR=     3.5000   IC=       .1150   OC=      .1670
DW=     .00432  DD=     4.0600   IH=       .4720   OH=      .6400
G=     04060    LB=     6.4000   LR=      2.5000   CR=    13.6500
RC=    2.3250   LC=    12.9000   LD=     12.0200   LH=    41.8000
LI=   25.5800   NC=   312        NR=   6           N=    4
NH=  36         FF=      .2000   AL=      90.00    CX=   254.2804
ME=   90.0000   FE=    80.0000   EC=      .04060   SC=     .06350
SE=    .10160   SR=     .05100   ZZ=   1           ZH=    203.62
KM=     .2000   ID=      .7600   LE=     71.0000   NE=   6
BF=     4000    BB=
POWER, WATTS                     HEAT REQUIREMENT, WATTS
  BASIC              35202.6016    BASIC                   60231.9844
  HEATER F.L.          997.9139    REHEAT                   1373.7683
  REGEN F.L.          1923.3396    SHUTTLE                  1935.7202
  COOLER F.L.         1019.1125    PUMPING                   203.8463
  NET                31262.2383    TEMP.SWING               2532.4609
  MECH FRIC.          3126.2244    CONDUCTION                203.6237
  BRAKE              28136.0156    FLOW FRIC.CREDIT        -1959.5837
---------------------------------- HEAT TO ENGINE           64521.8203
INDICATED EFF.%=   48.4522         FURNACE LOSS            16130.4551
OVERALL EFF.%=   34.8356           FUEL INPUT              80652.2734
---------------------------------------------------
HOT METAL TEMP  K=  922.2222     COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  849.8565   EFFEC.COLD SP.TEMP.K. =  353.4494
---------------------------------------------------
```

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=   2000.00   PS=   1000.00   ND=      30.00   TF=   1200.00
L1=     0.0000  TY=  135.0000   FX=    25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=   10.1609   DR=     3.5000  IC=      .1150   OC=       .1670
DW=    .00432   DD=     4.0600  IH=      .4720   OH=       .6400
G=     .04060   LB=     6.4000  LR=     2.5000   CR=    13.6500
RC=    2.3250   LC=    12.9000  LD=    12.0200   LH=    41.8000
LI=   25.5800   NC=   312       NR=  6           N=   4
NH=  36         FF=      .2000  AL=      90.00   CX=   254.2804
ME=   90.0000   FE=    80.0000  EC=     .04060   SC=      .06350
SE=    .10160   SR=     .05100  ZZ=  1           ZH=     194.83
KM=     .2000   ID=      .7600  LE=    71.0000   NE=  6
BF=     .4000   BB=
POWER, WATTS                       HEAT REQUIREMENT, WATTS
  BASIC                67612.1016   BASIC                 118928.5312
  HEATER F.L.           1927.4856   REHEAT                  2778.0645
  REGEN. F.L.           3147.8110   SHUTTLE                 1852.1472
  COOLER F.L.           1946.4116   PUMPING                  602.3567
  NET                  60590.3984   TEMP. SWING             9880.2656
  MECH. FRIC.           6059.0410   CONDUCTION               194.8324
  BRAKE                54531.3594   FLOW FRIC. CREDIT      -3501.3911
---------------------------------- HEAT TO ENGINE        130734.7969
INDICATED EFF.%=   46.3460          FURNACE LOSS           32683.6992
OVERALL EFF.%=   33.3691            FUEL INPUT            163418.4844
-----------------------------------------------------
HOT METAL TEMP. K=  922.2222    COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP.TEMP.K=  836.6948  EFFEC.COLD SP.TEMP.K. =  360.9674
-----------------------------------------------------
```

Table B.1 (continued)

Input and Output Printouts

```
ISOTHERMAL SECOND ORDER CALCULATION--
 PROG. ISO
 09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP=  2000.00   PS=   1400.00   ND=     30.00   TF=   1200.00
L1=    0.0000  TY=  135.0000   FX=   25.0000   OG= 1


CURRENT DIMENSIONS ARE:
DC=  10.1600   DR=    3.5000   IC=     .1150   OC=      .1670
DW=    .00432  DD=    4.0600   IH=     .4720   OH=      .6400
G=     .04060  LB=    6.4000   LR=    2.5000   CR=   13.6500
RC=   2.2250   LC=   12.9000   LD=   12.0200   LH=   41.8000
LI=  25.5800   NC=  312        NR=  6          N=    4
NH=  36        FF=     .2000   AL=    90.00    CX=  254.2804
ME=  90.0000   FE=   80.0000   EC=     .04060  SC=     .06350
SE=    .10160  SR=    .05100   ZZ=  1          ZH=    188.94
KM=    .2000   ID=     .7600   LE=   71.0000   NE=  6
BF=    .4000


POWER, WATTS                        HEAT REQUIREMENT, WATTS
  BASIC               91861.8906     BASIC                164954.7812
  HEATER F.L.          2651.8186     REHEAT                 3992.2964
  REGEN.F.L.           4117.2451     SHUTTLE                1796.1570
  COOLER F.L.          2677.4727     PUMPING                1011.6228
  NET                 82415.3594     TEMP. SWING           19046.0352
  MECH FRIC            8241.5371     CONDUCTION              188.9427
  BRAKE               74173.8281     FLOW FRIC.CREDIT      -4710.4409
---------------------------------- HEAT TO ENGINE       186279.3906
INDICATED EFF.%=    44.2429          FURNACE LOSS          46569.8437
OVERALL EFF %=   31.8549             FUEL INPUT           232849.2187
-----------------------------------------------------
HOT METAL TEMP  K=  922.2222      COOLING WATER INLET TEMP., K=  330.5555
EFFEC.HOT SP TEMP K=  828.4016    EFFEC.COLD SP.TEMP.K. =  366.9746
-----------------------------------------------------
```

The first step was to plot the minimum flow loss versus the speed squared. This plot is shown in Figure B.2. This relationship is linear and was easily fitted. This relationship allowed prediction of flow loss at relatively high pressures. The final step was to develop the correlation that would allow predictions at relatively low pressures. The change in the torque ratio between the highest value (high pressure) and the values at other pressures is shown in Figure B.3. In one attempt to bring the curves together, it was decided to divide the change by the speed. An average of these curves was fitted with a power curve. The curves are shown in Figure B.4. Taking into account both effects, the final equation was:

$$TQN = TQI * (.99862 - 9.14 \times 10^{-5} (SP)^2) (1 - 3.09 \times 10^{-3} (SP)(MPa)^{-1.841})$$

where TQN is net torque, TQI is indicated torque, SP is engine speed in Hertz, and MPa is engine pressure in MPa.

Validation of this equation consisted in using it to calculate the torque ratio for the 16 cases previously calculated.

The predictions were compared with the calculated results and plotted in Figure B.5. The error band fits were within the error expected from the actual fluid mechanic calculations. This method of estimating flow loss is reasonably accurate and saves computer time and space.

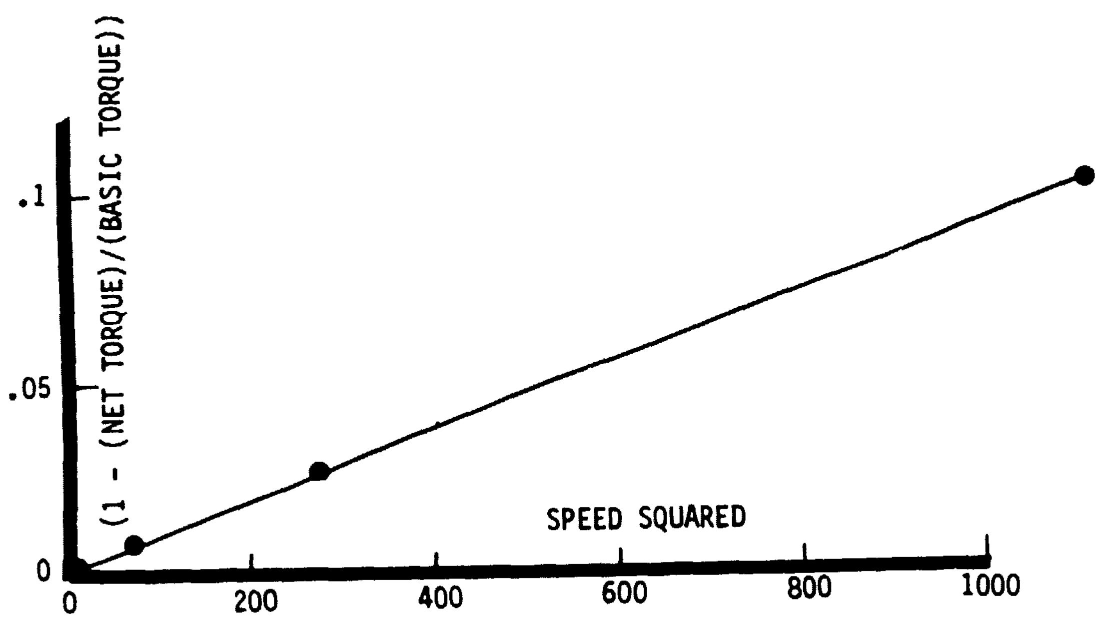

Figure B.2. Minimum Flow Loss Versus Speed Squared.

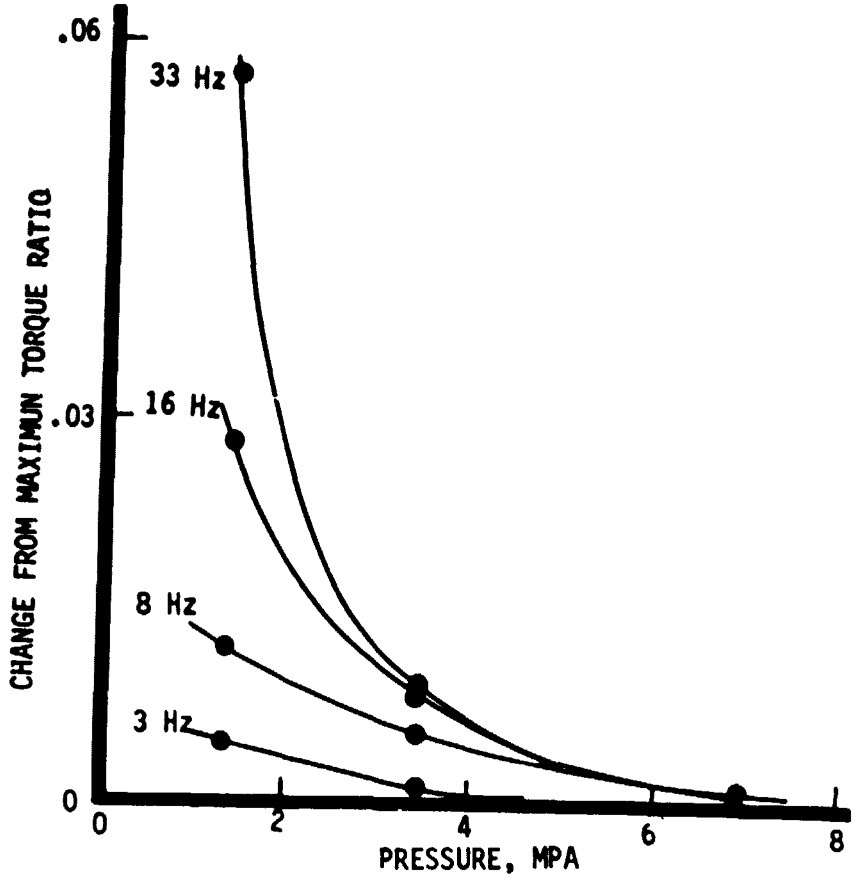

Figure B.3. Maximum Torque Ratio Change Versus Pressure.

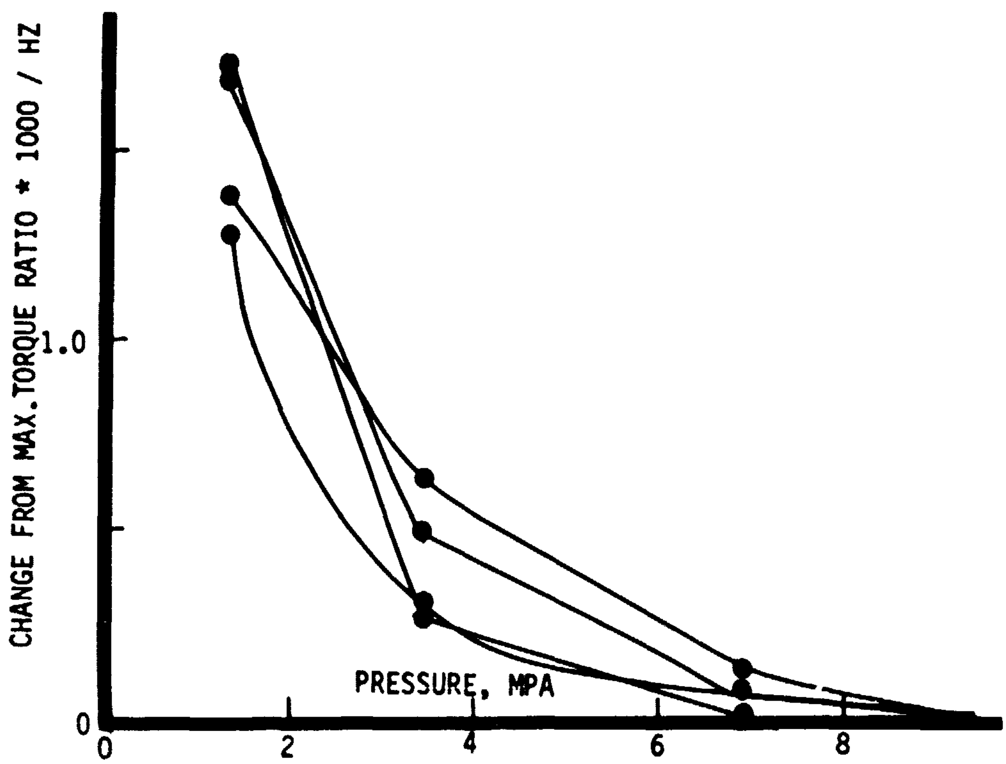

Figure B.4. Torque Curve Correlation.

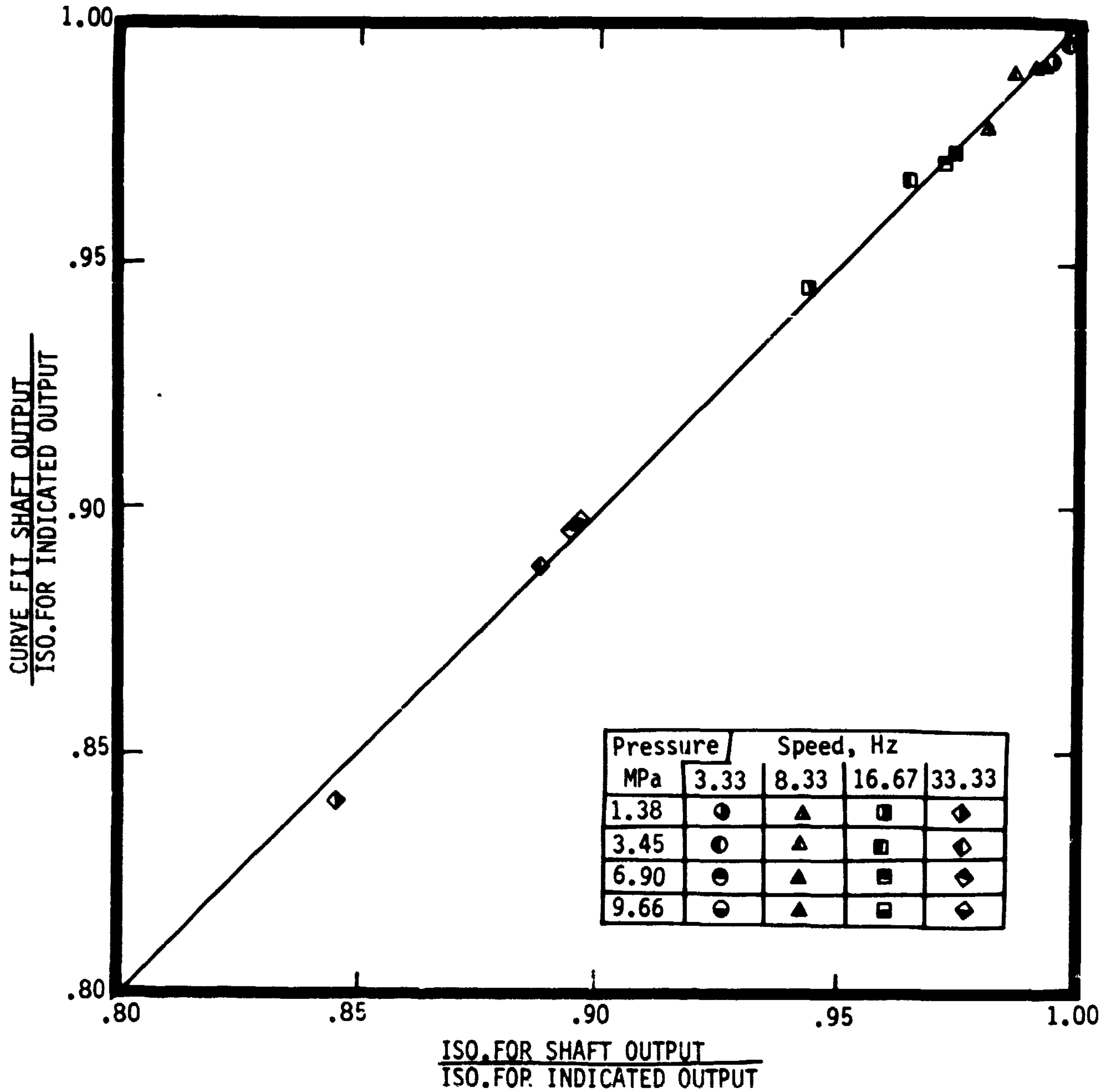

Figure B.5. Predictions Versus Actual Calculations.

APPENDIX C

GRAPHIC SUBROUTINES

The graphic subroutines listed and explained in this appendix were left out of the listing of CNTLB.FOR because they had already been included in the library for the Altos computer at Martini Engineering. Other computers will probably have different graphic packages, so an explanation of what each subroutine does is included. The subroutines are VECTOR, POINT and CLEAR. Also, an explanation of the subroutine ERASE given on lines 888 to 922 of CNTLB (see page 104) will be given. All of these use a machine language subroutine CONOUT. (See Table C.1 for a listing of CONOUT.) The Retrographics* modification to the Lear-Siegler ADM-3A terminal employs certain control codes to get between the different modes. This control chart is shown in Figure C.1. CONOUT is used to give the computer the signal in

Table C.1

MACHINE LANGUAGE LISTING OF CONOUT

```
            ENTRY   CONOUT
CONOUT:
            MVI     A,10H
            OUT     1DH
            IN      1DH
            ANI     00001100B
            CPI     00001100B
            JNZ     CONOUT
            MOV     A,M
            OUT     1CH
            RET
            END
```

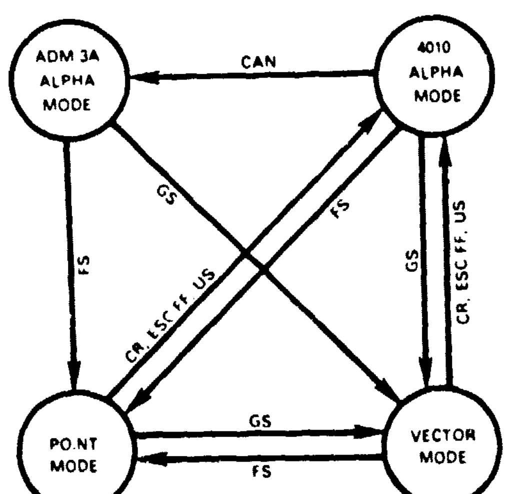

Figure C.1. Retrographics Control Scheme.

*Product of Digital Engineering Inc., 1787-K Tribute Rd., Sacramento, CA 95815.

the proper form to be recognized. Table C.2 shows the code that is used. The subroutines will now be explained.

Table C.2

CONTROL CODES

ASCII Code Name	Name in Subroutine	ASCII Decimal Number	Function
CAN	CA	24	Move from 4010 alpha to ADM-3A alpha.
EM	UY	25	Clear screen.
FS	FS	28	Move to point mode.
GS	GS	29	Move to vector mode.
US	US	31	Move from vector mode to 4010 alpha.
ESC	ES	27	Sets data level to black
DEL	DE	127	
a	AA	97	With ES sets data level to white.

VECTOR

The subroutine VECTOR draws a straight line. It is listed in Table C.3. It has four arguments. They are defined as follows:

JX = X axis coordinate of start of vector.
JY = Y axis coordinate of start of vector.
KX = X axis coordinate of end of vector.
KY = Y axis coordinate of end of vector.

As for any subroutine, the position is important and the names can be changed. These coordinates are integers. The main program scales the values to be plotted so that the X axis coordinate is between 0 and 1023 and the Y axis coordinate is between 0 and 779. (See Figure C.2.)

In line 757 of Table C.3 the integers are defined. In line 758 the values needed from Table C.2 are defined. In line 759 the control code GS is sent to go from the ADM-3A alpha mode to the vector mode (see Figure C.1). In lines 760 and 761 the Y coordinate of the start of the vector is split into its upper and lower components according to directions. In lines 762 and 763 the same thing is done for the X coordinate of the start of the vector. In lines 764 to 767 these four numbers are entered. Lines 768-770 cause a slight delay in the program to allow the entering to be complete.

From lines 771 to 780 the same thing is done for the end coordinate of the vector. Once the computer has both coordinates, it draws a straight line between them. The timing loop (lines 779 to 781) is needed to allow the computer to draw the line before it goes on to something else. The time

Table C.3

```
C SUBROUTINE FOR DRAWING A VECTOR ON THE SCREEN
          SUBROUTINE VECTOR(JX,JY,KX,KY)
          INTEGER*1 GS,US,YH,YL,XH,XL,CA
          DATA GS,US,CA/29,31,24/
          CALL CONOUT(GS)
          YH=JY/32+32
          YL=MOD(JY,32)+96
          XH=JX/32+32
          XL=MOD(JX,32)+64
          CALL CONOUT(YH)
          CALL CONOUT(YL)
          CALL CONOUT(XH)
          CALL CONOUT(XL)
          DO 10 I=1,200
          M=I+1
10        CONTINUE
          YH=KY/32+32
          YL=MOD(KY,32)+96
          XH=KX/32+32
          XL=MOD(KX,32)+64
          CALL CONOUT(YH)
          CALL CONOUT(YL)
          CALL CONOUT(XH)
          CALL CONOUT(XL)
          DO 20 I=1,200
          M=I+1
20        CONTINUE
          CALL CONOUT(US)
          CALL CONOUT(CA)
          RETURN
          END
```

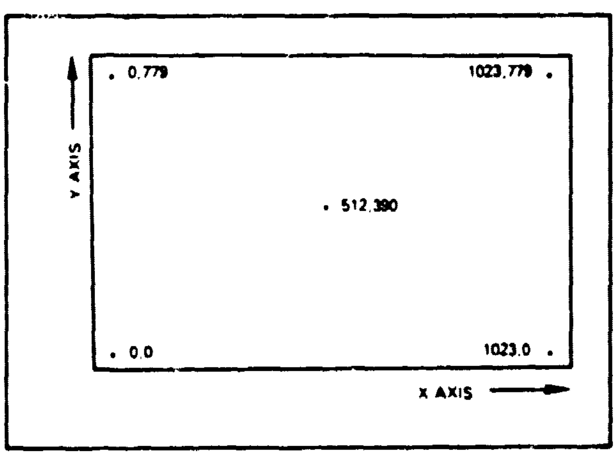

Figure C.2. Coordinate Numbering for Graphics.

delay used here works for even the longest line.

Lines 782 and 783 get control back to the ADM-3A alpha mode by going through the 4010 alpha mode. (See Figure C.1 and Table C.2.)

POINT

The subroutine POINT puts a point on the screen. It is listed on Table C.4. It has two arguments:

JP = X axis of point
JQ = Y axis of point

Table C.4

```
727: C SUBROUTINE FOR POINT GRAPHICS
728:         SUBROUTINE POINT(JP,JQ)
729:         INTEGER*1 FS,US,CA,YH,YL,XH,XL,UY
730:         DATA FS,US,CA,UY/28,31,24,25/
731:         CALL CONOUT(FS)
732:         YH=JQ/32+32
733:         YL=MOD(JQ,32)+96
734:         XH=JP/32+32
735:         XL=MOD(JP,32)+64
736:         CALL CONOUT(YH)
737:         CALL CONOUT(YL)
738:         CALL CONOUT(XH)
739:         CALL CONOUT(XL)
740:         CALL CONOUT(US)
741:         CALL CONOUT(CA)
742:         RETURN
743:         END
```

As for any subroutine the positions of the arguments are important and the names can be changed. These coordinates are integers scaled as shown in Figure C.2. In lines 729 and 730 of Table C.4 the integers and the data are defined. In line 731 the control code FS is sent to get control into the point mode. (See Figure C.1.) In lines 732 to 739 the upper and lower component of each coordinate is calculated and sent in the proper order. A point corresponding to this coordinate lights up on the screen. Lines 740 and 741 return control to the ADM-3A alpha mode via the 4010 alpha mode (see Figure C.1).

CLEAR

The subroutine CLEAR erases the entire graphic screen without touching the ADM-3A alpha screen which is superimposed. CLEAR has no arguments. A listing is shown in Table C.5. In Table C.5, lines 746 and 747 initialize as usual. In line 748 the control code GS is sent to get the control into the vector mode. In this mode sending the control code EM (UY in our subroutine)(see Table C.2) clears all the screen. Lines 750 and 751 get control back to ADM-3A alpha mode in the usual way.

Table C.5

```
C SUBROUTINE FOR CLEARING VECTOR MODE SCREEN
          SUBROUTINE CLEAR
          INTEGER*1 GS,UY,US,CA
          DATA GS,UY,US,CA/29,25,31,24/
          CALL CONOUT(GS)
          CALL CONOUT(UY)
          CALL CONOUT(US)
          CALL CONOUT(CA)
          RETURN
          END
C
```

ERASE

The subroutine ERASE draws a series of black lines from X coordinate 710 to 1013. The black lines are drawn in the Y direction from 2 to 777. On page 104 lines 889 and 890 initialize things. Line 891 starts the do loop. Line 892 gets control to the vector mode. Lines 893 and 894 together set the data level to black from white. Lines 895 to 914 draw a black line. Lines 915 and 916 set the data level back to white. Lines 917 and 918 get back to the ADM-3A alpha mode. Line 919 is the end of the do loop.

An attempt was made to shorten this subroutine by putting the do loop in the vector mode part of the program, but this did not work. The subroutine requires 6 seconds to clear this part of the screen. More efficient subroutines for clearing part of the screen can probably be worked out, but this subroutine was not a vital part in the total computing time.

Graphic output greatly speeds the comprehension of the computed results. It should always be used if available for this type of analysis.